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NBS TECHNICAL NOTE 1182

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

AC Voltage Calibrations for the 0.1 Hz to 10 Hz Frequency Range

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AC Voltage Calibrations for the 0.1 Hz to 10 Hz Frequency Range

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NBS technical note

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The development of voltmeters to meet the need for rms voltage measurements in the infrasonic frequency range is discussed as well as the need to trace these measurements to the U.S. legal unit of voltage. A new method for supporting voltage measurements in the 0.1 Hz - 10 Hz range was described in a 1979 paper and is discussed further. The principles of the method are embodied in detailed procedures given for calibrating sine-wave voltage standards and rms voltmeters over the 0.1 Hz - 10 Hz frequency range, using the NBS AC Voltmeter/Calibrator. The sine-wave calibrator of this instrument, used for these calibrations, has an accuracy of 0.020 percent over the 0.5 mV - 7 V range.

Key words: ac voltage calibrations; ac voltage calibrators; ac voltage standards; infrasonic voltage measurements; low-frequency voltage measurements; rms voltmeters.

1. INTRODUCTION

Calibrated vibration transducers are required in laboratories and test facilities to determine the acceleration of vibration exciters, tables, and fixtures. They are also used to measure the vibrations in many other types of machines and structures, including prototype models of military, space, and commercial vehicles undergoing qualification testing. In past years, calibrations of these transducers at frequencies below 2 Hz were either omitted or performed with uncertain accuracy. This was because the voltmeters available for measuring the transducer outputs at these frequencies had questionable accuracy and excessively long response times (15 to 20 periods of the measured voltage).

In 1976, an rms digital voltmeter (DVM) was developed at the National Bureau of Standards (NBS) to support vibration measurements over the 0.1 Hz - 50 Hz range.[1] It was designed to measure voltages from 2 mV to 10 V with an uncertainty of approximately 0.1 percent of reading. The maximum response time of 40 seconds corresponds to four periods of the lowest frequency signal that can be measured. Since the means for calibrating the voltmeter to the required accuracy did not exist, a voltage calibrator was developed and incorporated

[1]This work was supported, in part, by the DC and Low Frequency Calibration Coordination Working Group of the Department of Defense.

into the same instrument. This calibrator, providing bipolar dc voltages and sine-wave voltages at frequencies of 0.1, 0.2, 0.5, 1, 2, 10, and 50 Hz, was intended not only for calibration of the companion voltmeter but also for the calibration of other low-frequency voltmeters.

During the 1976-77 period, the NBS AC Voltmeter/Calibrator was used at the Metrology and Calibration Centers of Redstone Arsenal (Army) and Newark Air Force Base, as well as the Vibration Section at NBS, to measure vibration transducer outputs and to calibrate other ac voltmeters [1][2]. Except for the need of a 5-Hz calibration frequency,[3] the instrument met all present and expected future requirements for support of voltage measurements at very low frequencies.[4] Consequently, a detailed instruction manual and an archival paper were written to facilitate reproduction of the instrument [2]. A commercial instrument based on the NBS design later became unfeasible because the ac voltmeter portion utilizes a multi-junction thermal converter (MJTC), which has been available only in limited quantities from one manufacturer. Subsequent to the development of the NBS AC Voltmeter/Calibrator, at least two other instruments have been developed which can measure voltages at infrasonic frequencies. NBS has developed a Low Frequency AC Samping Voltmeter which has approximately 0.1 percent uncertainty and a nominal maximum response time of two periods of the lowest frequency signal (0.1 Hz) that can be measured [3,4].[5] Also, a large instrumentation manufacturer has developed a multimeter with a sampling voltmeter, operable down to 0.1 Hz or lower. However, the accuracy and response time of the voltmeter depend upon the frequency of the measured voltage.

As the number of ac voltage measurements in the 0.1 Hz - 10 Hz range increases, because of the greater availability of suitable voltmeters, the need increases for tracing these measurements to the U.S. legal unit of voltage. Selecting the best method for effecting this traceability is discussed next.

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[2]Numbers in brackets refer to the literature references listed at the end of this report.

[3]This calibration frequency was added later.

[4]Commercial voltage calibrators operate at frequencies down to 10 Hz and can be calibrated using conventional ac-dc transfer measurements. Also, a number of commercial voltmeters function satisfactorily above 10 Hz; therefore, the voltage measurement and calibrator capability above 10 Hz were not considered vital.

[5]Six of these units have been made by NBS, and supplied to each of the DoD metrology laboratories. They were calibrated by using the NBS AC Voltmeter/Calibrator as a reference standard.

2. A METHOD FOR INFRASONIC VOLTAGE MEASUREMENTS

Standards laboratories calibrate ac voltage standards against dc voltage standards, using thermal voltage converters (TVCs) to make the ac-dc voltage comparisons. Calibrations of the dc voltage standards and TVCs are traceable to reference standards maintained by NBS. Theoretical and practical limitations arise in calibrating TVCs (measuring their ac-dc difference), and employing them to make calibrations at the lower infrasonic frequencies [5].[6] These limitations cause the calibrations to be slow, costly, and inaccurate, particularly at frequencies below ~2 Hz. For these reasons, a new method was proposed in [5] for supporting ac voltage measurements below 10 Hz, which supplements the existing method as shown in figure 1. The primary objective of the new procedure is to make it feasible to equip standards laboratories with easily calibrated multi-range sine-wave standards, which operate at frequencies of 0.1, 0.2, 0.5, 1, 2, 5, and 10 Hz. These voltage sources would be used mostly to calibrate voltmeters at these frequencies over the voltage range of approximately 0.5 mV - 7 V rms.[7]

The proposed equipment and procedures for testing a multi-range voltage source are described in sections IV and V of [5]. Central to the method is a single voltage level sine-wave reference source with frequencies of 0.1, 0.2, 0.5, 1, 2, 5, and 10 Hz, whose amplitude variation with frequency (frequency response) is calibrated and has excellent long-term stability. This unit serves as a voltage transfer standard. By adjusting the output of the multi-range source to be approximately the same as the voltage level of the reference, the frequency response of the source can be determined from ac-ac comparisons, using an rms transfer voltmeter. Following this step, the voltage level at each frequency is established by calibrating the unit at 10 Hz, using a dc voltage standard and a TVC to make an ac-dc transfer measurement.

Except for the rms voltmeter contained in the NBS AC Voltmeter/Calibrator, existing rms voltmeters do not have the necessary high resolution and small differential nonlinearity to make ac-ac comparisons for calibration work.[8] Until rms voltmeters suitable

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[6]For convenience, reference 5 is included at the end of this report.

[7]Present commercial ac voltage calibrators either have insufficient accuracy over this voltage range or only operate above 10 Hz.

[8]A transfer voltmeter must be able to measure voltage differences as small as 20 ppm of the measured value, both voltages being of the same frequency. The ac-dc difference and accuracy of the voltmeter are not critical, however.

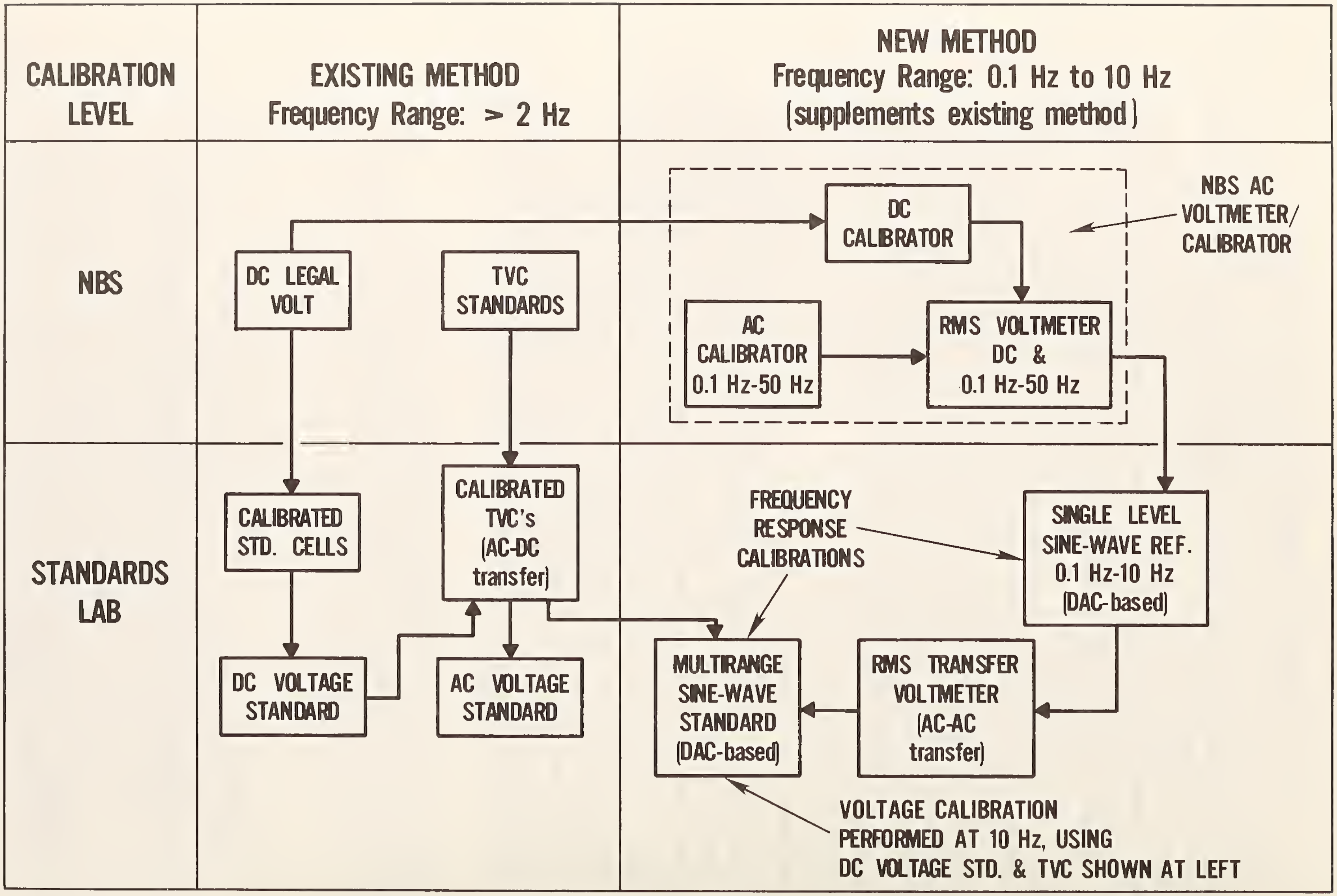

Figure 1. New method for supporting ac voltage measurements at frequencies below 10 Hz.

for this work become available, calibration of multi-range sine-wave voltage sources[9] and rms voltmeters will be performed at NBS. Procedures for these calibrations are discussed in sections 4 and 5.

Since the ac calibrator portion of the NBS AC Voltmeter/Calibrator (see fig. 1) would be a suitable multi-range voltage standard for use by standards laboratories, the detailed design of this circuit is given in appendix B. The methods used to calibrate the unit are included in the calibration procedure described in the next section.

3. CALIBRATION OF NBS AC VOLTMETER/CALIBRATOR

As described in [2] and [5], the NBS AC Voltmeter/Calibrator consists of an rms digital voltmeter and a calibrated voltage source which can function as either a dc or ac voltage calibrator. The rms voltmeter consists of an input amplifier, rms/dc converter, and dc DVM.

The ac voltage calibrator is used to calibrate ac voltmeters and is used in conjunction with the rms voltmeter to calibrate ac voltage sources. The procedure used to calibrate the ac voltage calibrator is shown in figure 4 of [5]. To perform this calibration, the frequency response of the ac calibrator and the ac-dc difference of the rms/dc converter must be known from prior measurements. All of these calibrations are listed below and are discussed in this section.

(1) Frequency response and voltage calibrations of the ac voltage calibrator.

(2) Calibration of the laboratory dc voltage standard (standard cell).

(3) Calibration of the dc calibrator.

(4) AC-DC difference calibration of the rms/dc converter.

The errors associated with the items listed above all contribute to the estimated uncertainty assigned to the ac calibrator voltage and will be summarized after these calibrations have been described.

Several refinements were made recently to simplify the task of calibrating the AC Voltmeter/Calibrator and to improve its overall performance. These changes are also discussed in this section.

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[9]Assuming that the voltage standards employ a D/A converter for the sine-wave generation, a frequency response (relative voltage) calibration is preferable to a conventional voltage calibration.

3.1 Calibration of AC Voltage Calibrator

Calibration of the ac voltage calibrator consists of two calibrations: (1) a frequency response calibration in which the calibrator voltages at 5, 2, 1, 0.5, 0.2, and 0.1 Hz are compared with the voltage at 10 Hz, and (2) a voltage calibration at 10 Hz.

3.1.1 Frequency Response Calibration of AC Calibrator

The frequency response of the ac calibrator was originally determined using peak-to-peak and rms measurements, the latter being made with the rms voltmeter and limited to the 1 Hz - 10 Hz range [2]. Average-value measurements were later combined with the above results [5]. Since the peak-to-peak method uses a storage oscilloscope to exhibit the voltage peaks, the measurements are somewhat subjective and are considered less reliable than the average-value measurements; therefore, only the latter (along with limited rms measurements) are now used for the frequency response calibrations. The precision rectifier-filter circuit used for these measurements is represented by figure 5 of [5]. This circuit and associated power supply are contained in a separate shielded enclosure. The justification for basing the rms frequency response of the ac voltage calibrator on average-value (or peak-to-peak) measurements is given in [5].

Figure 2 shows the front panel operating controls of the NBS AC Voltmeter/Calibrator. The 5 Hz and 0.1 Hz frequencies are selected with the CAL FREQ switch in the 10 Hz and 0.2 Hz positions, respectively, using the rear panel "5 Hz-10 Hz" and "0.1 Hz-0.2 Hz" switches (see fig. 3). For average-value measurements, the precision rectifier circuit is connected between the CAL OUT terminals and the AVE. VOLT. IN terminals (rear panel) with the PREC RECT-INTERNAL switch in the PREC RECT position. In this switch position, the rms/dc converter is disconnected and the output of the precision rectifier is connected to the input (point o) of the voltmeter's low pass filter (see fig. 2 of [5]). A dc voltage level of 5 V (nominal) at this terminal corresponds to a full-scale indication of the voltmeter. Therefore, the full-scale voltmeter reading is normalized to whatever range is selected by the V-RANGE-MV switch. Since full-scale readings of 10000.0, 5000.0, 2000.0, 1000.00, --- result from range selections of 10, 5, 2, 1, --- volts, it is seen that the best resolution is obtained with the 10, 1, 0.1 or 0.01 V ranges. (Unless indicated otherwise, the PERIOD is set to 10 for all measurements.) The 10 V range has been arbitrarily selected for the frequency response measurements. Because the rms/average ratio for a sinewave is ~1.11, the ac calibrator should be set to approximately 5.55 V to yield a full-scale output of 5 V from the rectifier-filter circuit. (The "÷100" attenuator switch, not shown in fig. 2, should be kept in the OUT position. Also, the FUNCTION switch should be in the MEAS position.)

Figure 2. Front panel view of NBS AC Voltmeter/Calibrator.

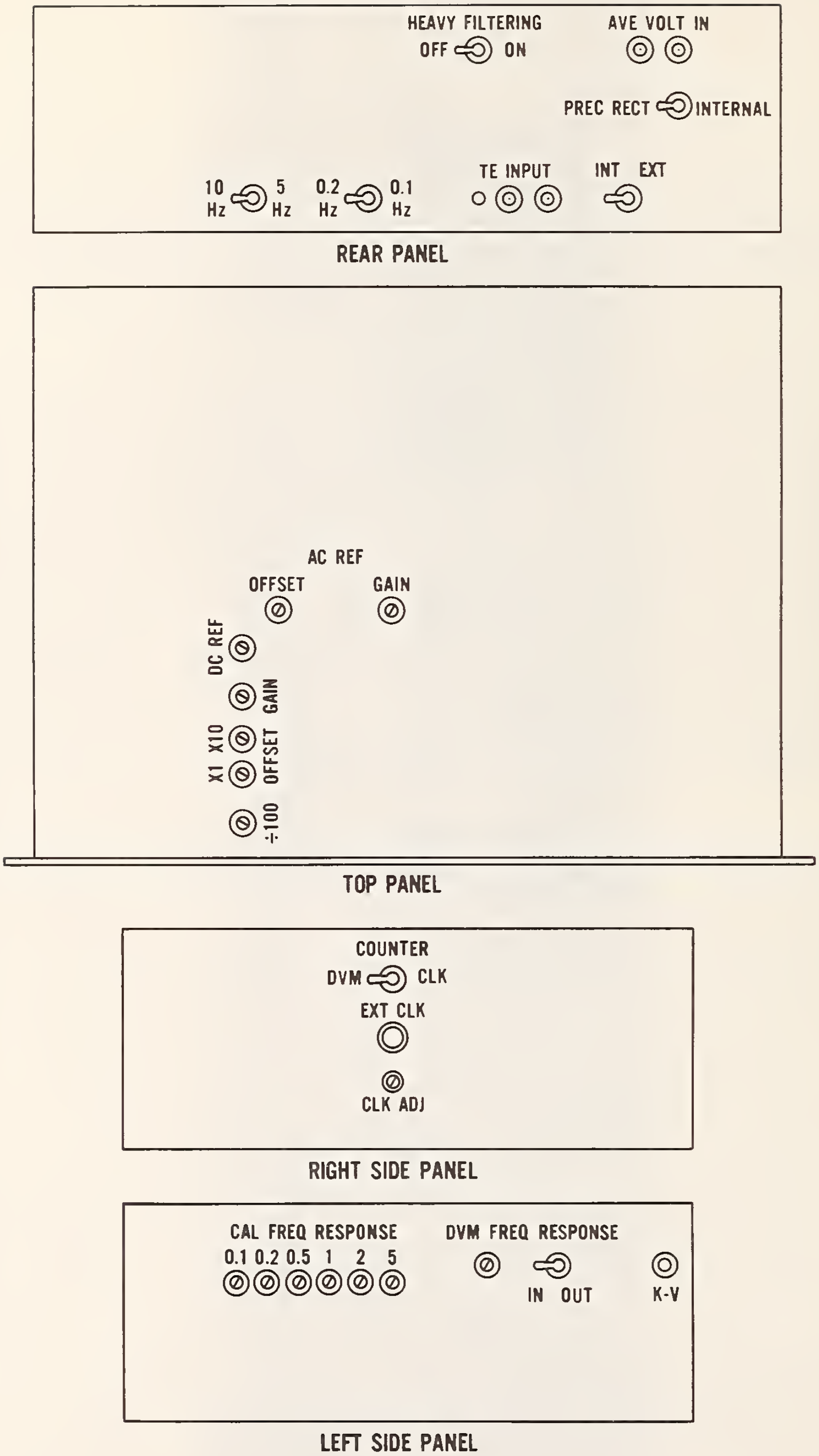

Figure 3. Controls and connectors on rear, top, and side panels of AC Voltmeter/Calibrator.

The dc DVM employed in the rms voltmeter of the NBS AC Voltmeter/Calibrator (fig. 2 of [5]) consists of a V/F converter and a counter-timer which counts the output pulses from the V/F converter over periods of 1 s or 10 s (PERIOD set to 1 or 10), determined by a crystal-controlled oscillator. An integrating voltmeter was used to effectively reduce the ripple in the output voltage from the low-pass filter, to minimize fluctuations in the displayed voltage. The frequency of the ripple voltage in the outputs of both the rms/dc converter and the precision rectifier circuit is twice the frequency of the input voltage to these circuits. If the counter period (integration period) includes an integral number of ripple periods, the ripple in the dc voltage applied to the dc DVM will integrate to zero [2].[10] Therefore, fluctuations in the indicated voltage from ripple are zero for frequencies of 0.05, 0.1, 0.15, --- Hz, which include the nominal values of the calibrator frequencies. (An integration period of 10 s must be used for frequencies of 0.5 Hz and less.) To allow for some deviation from these frequencies by the AC Voltage Calibrator, ripple filtering in the low-pass filter and rms/dc converter can be increased (with respect to the original design) using the HEAVY FILTERING switch on the rear panel of the AC Voltmeter/Calibrator.

The effect of this filtering on rms measurements will be discussed later. When the precision rectifier is used, the additional filtering limits the measured peak-to-peak ripple voltage to ±0.30 percent of the dc voltage applied to the dc DVM when the input frequency is near 0.1 Hz. (The ripple voltage is much less near the higher calibrator frequencies.) The computed maximum peak-to-peak fluctuation in the DVM readings is approximately ±30 ppm for each percent deviation in frequency from 0.1 Hz. For all calibration work, the calibrator frequencies should be held within ±0.05 percent of their nominal values so that the effect of ripple on DVM readings is negligible (±1.5 ppm or less, based on the preceding statements). The calibrator frequencies are at their nominal values when the clock frequency, from which they are derived, is 6400 Hz. The clock frequency is easily held with ±0.05 percent of 6400 Hz, since observed daily frequency variations are usually less than ±2 Hz (±0.03%). The frequency can be adjusted by the CLK ADJ pot and is displayed by the counter-timer when the COUNTER switch is in the CLK position (see fig. 3).

Worst-case DVM reading errors caused by ripple voltage can be avoided by using the average of several successive readings instead of a single reading, since the ripple integrations in the dc DVM will vary in size and usually are of both polarities. Therefore, the average value is more accurate than the worst-case single reading

[10] In other words, the ripple voltage integrates to zero if a time interval equal to two counter periods includes an integral number of input signal periods.

value. Unless indicated otherwise, maximum filtering (FILTER FREQ switch in position L and the HEAVY FILTERING switch on) should be used for all calibration work. With maximum filtering, the DVM settling time to within 5 ppm is about 2 minutes. This response time must be considered when devising the measurement procedure for determining the calibrator frequency response.

Table 1 shows a typical set of average-value measurements which was used to evaluate the frequency response of the ac calibrator. The DVM readings are represented by V_f or V_{10}, where the subscripts denote the frequency of the voltage being measured. Calibrator frequencies are switched approximately every 3 minutes, allowing 2 minutes for voltmeter settling and 1 minute for recording six readings. If the first-recorded value is not repeated, it should be discarded, since this probably indicates lack of complete settling by the DVM. Successive numbers represent the least significant digit of successive DVM readings. The 0.5, 0.2, and 0.1 Hz measurements are compared with the succeeding 10 Hz measurement to minimize the time periods between readings that are compared, thus minimizing the effect of voltmeter drift.

Table 1. Typical set of average-value measurements used to evaluate the frequency response, $V_f - V_{10}$, of the ac voltage calibrator. The nominal value of V_f and V_{10} is normalized to 1000 units.

Elapsed time(min)	Frequency(f)	DVM reading(V_f)[a]	Mean value	V_f-V_{10}
0	10 Hz	1000.47,8,8,8,8,7	1000.477	
3	5	1000.48,8,8,8,8,8	1000.480	+0.003
6	2	1000.48,8,8,8,8,8	1000.480	+0.003
9	1	1000.48,8,8,7,8,8	1000.478	+0.001
12	0.5	1000.48,8,9,8,9,8	1000.483	+0.005
15	0.2	1000.48,8,8,9,8,8	1000.482	+0.004
18	0.1	1000.48,7,7,7,8,8	1000.475	-0.003
21	10	1000.48,8,7,8,8,8	1000.478	

[a]Successive numbers represent the least significant digit of successive readings.

For routine calibrations of the frequency response, it is planned to use the averages $\overline{(V_f - V_{10})}$ from two sets of measurements like those shown in table 1. In order to hold the magnitude of $(V_f - V_{10})$ near zero, frequency response adjustments have been added recently. If $\overline{(V_f - V_{10})}$ exceeds ±10 ppm for any frequency, the appropriate CAL FREQ RESPONSE pot should be adjusted to minimize the voltage difference (see fig. 3).

The estimated standard deviation of the measurement process is based on 15 sets of measurements, divided evenly among three groups. One group of measurements was made after the frequency response adjustments were added. A second group was made before the adjustments were provided. The third group of sets was obtained from the Naval Air Test Center, Patuxent River, MD (NATC) calibrator, which is based on the NBS design without frequency response adjustments. The maximum magnitude of $(V_f - V_{10})$ was approximately 5, 27, and 12 ppm, respectively, for the first, second, and third groups of sets. Although the statistical populations corresponding to the three groups have different values of $(V_f - V_{10})$, their standard deviations should be approximately equal, since all three calibrators had nearly identical electrical and mechanical designs. Therefore, a worst-case pooled estimate of the standard deviation (s_p), based on these three groups (15 sets) of measurements, will be used as the estimated standard deviation of a $(V_f - V_{10})$ measurement. The largest pooled estimate of the standard deviation is 4.4 ppm and occurs for a frequency equal to 0.5 Hz.

The estimated imprecision in $\overline{(V_f - V_{10})}$, obtained from N sets of measurements, can be expressed by $(s_p/\sqrt{N})t$, where t is Student's t, based on 2 degrees of freedom and a selected confidence level of 0.99. If $\overline{(V_f - V_{10})}$ is determined from two sets of measurements, the calculated imprecision is approximately 10 ppm. As mentioned previously, V_f will be readjusted if $\overline{(V_f - V_{10})}$ is larger than ±10 ppm. A control chart (fig. 4) will be kept showing calibration dates and the value of $\overline{(V_f - V_{10})}$ before being reset.

3.1.2 Voltage Calibration of AC Calibrator

The voltage level of the ac voltage calibrator is established by comparing the ac calibrator voltage at 10 Hz with the dc calibrator voltage, using the rms voltmeter as a transfer standard. For these ac-dc comparisons, the PREC RECT-INTERNAL switch is set to the INTERNAL position, HEAVY FILTERING is switched to OFF, and the FILTER FREQ switch set to L. Also, the PERIOD is set to 10 to yield maximum voltmeter resolution, and the DVM FREQ RESPONSE switch should be in the OUT position.

Before making ac-dc comparisons, the dc offset voltage of the calibrator buffer amplifier should be adjusted to a minimum value as follows. Set the CAL VOLTS dial to all zeros, the RANGE switch to 1 and the FUNCTION switch to INT AC CAL. Then, using a sensitive null

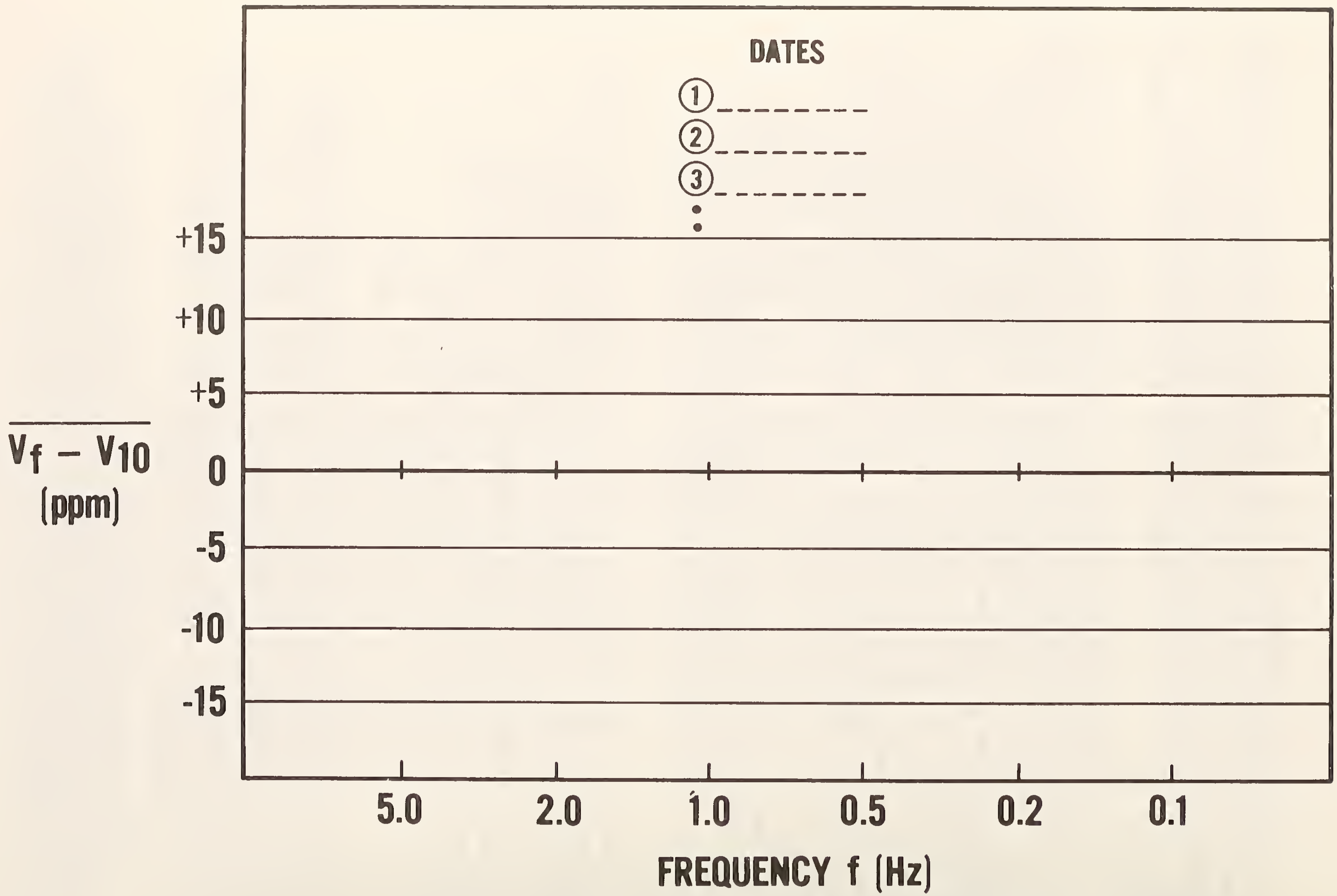

Figure 4. AC calibrator frequency response calibrations from average-value measurements. Calibrator voltages, V_f, at 5, 2 ---- Hz are compared with 10 Hz value. If $\overline{(V_f - V_{10})}$ exceeds ±10 ppm for any frequency, adjustment is made to minimize value.

detector, adjust the X1 OFFSET for a minimum voltage (<1 μV) at the CAL OUT terminals. With the RANGE at 10, adjust the X10 OFFSET for a minimum voltage (<10 μV). Following these adjustments, set the CAL FREQ to 10 Hz, CAL VOLTS to 5.000000, and the V-RANGE-MV switch to 10 V. Also, connect the CAL OUT terminals to the TE INPUT terminals with a coaxial cable and set the TE switch to EXT. Compare the ac calibrator voltage with the dc calibrator voltage (average of both polarities) as shown in table 2.

Table 2. A comparison between ac and dc calibrator voltages, applied directly to the rms/dc converter (TE INPUT). The FUNCTION and CAL columns are switch positions on the AC Voltmeter/Calibrator. The averages of ac and dc mean values are used for V_{ac} and V_{dc}. The nominal value of the DVM readings is normalized to 1000 units.

Elasped time(min)	FUNCTION INT CAL	CAL	DVM readings	Mean value	$V_{ac} - V_{dc}$
0	AC		1006.64,4,4,4,3,4	1006.638	
3	DC	+	1006.64,4,4,4,3,3	1006.637	0.6365-0.6235 = 0.013
6	DC	-	1006.61,1,1,1,1,1	1006.610	
9	AC		1006.64,3,4,3,4,3	1006.635	

For routine ac-dc difference calibrations, it is planned to use the average $\overline{(V_{ac} - V_{dc})}$ from three comparisons like the one shown in table 2. If $\overline{(V_{ac} - V_{dc})}$ exceeds ±20 ppm, the AC REF GAIN should be adjusted for a minimum difference. The estimated standard deviation s, of a comparison, is 7.0 ppm, obtained from 13 comparisons. Using the expression $(s/\sqrt{N})t$ to calculate the imprecision of $\overline{(V_{ac} - V_{dc})}$ yields approximately 12 ppm, where N is 3 and Student's t is based on 12 degrees of freedom and a confidence level of 0.99. Since $\overline{(V_{ac} - V_{dc})}$ will be readjusted if it is larger than ±20 ppm, the maximum estimated systematic error is ±20 ppm. A control chart (fig. 5) will be kept showing calibration dates and the value of the ac-dc difference before the AC REF GAIN is readjusted.

The dc offset of the function generator used in the sine-wave reference should be checked approximately every three years. It can be measured at pin 11 of the function generator with the DPDT switch in the ZERO position (see fig. B-2). The switch and offset adjustment

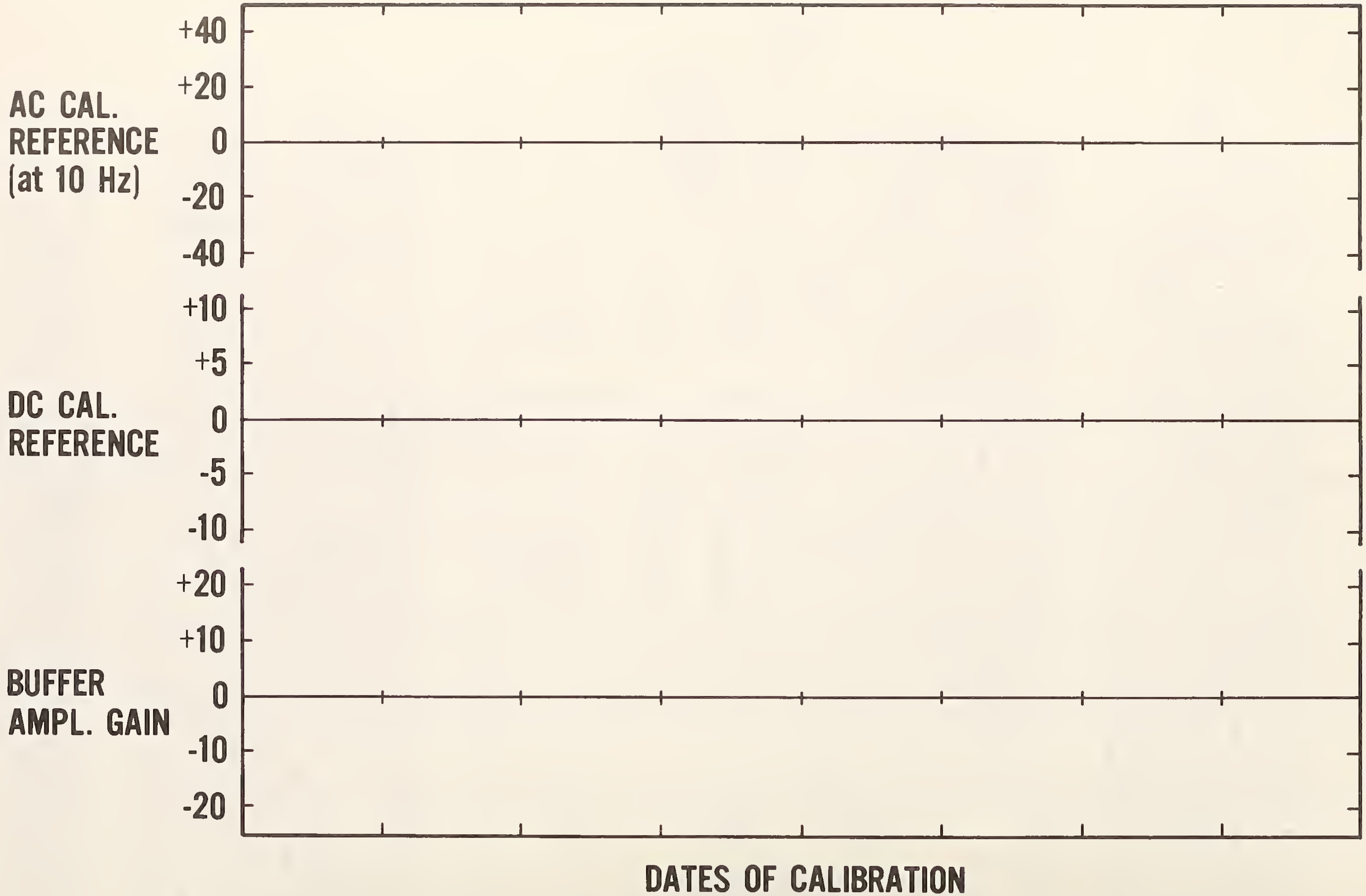

Figure 5. Drift (ppm) between calibrations of ac and dc calibrator references and buffer amplifier gain (X10 range). The ac voltage reference is not readjusted unless its drift exceeds ±20 ppm.

(R21) are accessed by removing the top panel. Adjustment of the offset is non-critical and is seldom required. Measurements show that an offset as large as ±200 μV contributes less than ±1 ppm to the rms value of the 1 V ac reference. A dc offset has a much larger effect on the average value of a sine wave; however, an offset voltage affects all calibrator frequencies the same and has no affect on frequency response measurements.

The measured temperature coefficient of the ac voltage reference is approximately +3 ppm/°C. Therefore, the imprecision for a 2°C range is ±6 ppm.

3.2 Calibration of the Standard Cells

The basic laboratory voltage standard to be used for calibrating the dc voltage calibrator is a set of four saturated standard cells, housed in a temperature-controlled standard cell enclosure and located near the AC Voltmeter/Calibrator. The cell voltages are fed to the NBS Volt Facility via a cable to facilitate in situ calibration. It is planned to calibrate the cells at least once a year. Calibrations performed in January and November of 1982 show a maximum drift of 0.4 ppm for this 10-month period.

3.3 Calibration of the DC Calibrator

The voltage of one of the calibrated standard cells (approx. 1.01815 V) is transferred to a "working" reference, using a null detector for the voltage comparison. A stable, 10 V laboratory reference with seven decade resolution (1 μV) is suitable for the working reference. The null detector should have approximately 140 dB common mode rejection and at least 1 MΩ input impedance. The detector is used for all voltage comparisons and offset voltage (zero) measurements described in this section.

A laboratory Kelvin-Varley (K-V) divider is used to "step" the reference voltage to the appropriate level for calibrating the dc reference, buffer amplifier, and ÷100 attenuator of the calibrator. The K-V divider should have seven-digit resolution and a linearity of 0.1 ppm of input for dial settings between 1.0 and 0.1.

To calibrate the dc reference and buffer amplifier gain, set the CAL VOLTS dial to 0000000 and the FUNCTION switch to INT AC CAL. With the RANGE at 1, adjust the X1 OFFSET for minimum voltage (<1 μV) at the CAL OUT terminals. With the RANGE at 10, adjust the X10 OFFSET for minimum CAL OUT voltage (<10 μV). Return the RANGE to 1 and set the FUNCTION switch at INT DC CAL, CAL at + and CAL VOLTS at .99999910 (last digit set to 10). Set the K-V divider to the reciprocal of the standard cell voltage (approx. .9821700) and connect its input to the laboratory reference. Then, adjust the DC REF pot so that the calibrator voltage equals the K-V divider output

voltage. The gain of the buffer amplifier is adjusted with RANGE at 10, CAL VOLTS at 5.000000, and the K-V divider set to the ratio of the standard cell voltage to 5 V (approx. .2036300). With the K-V divider input connected to the CAL OUT terminals, adjust the X10 GAIN so that the divider output voltage equals the laboratory reference voltage.

In order to minimize errors in the ac and dc calibrator voltages at small signal levels (< 50 mV) caused by extraneous signal and noise pickup, voltage offsets and Kelvin-Varley divider (see fig. 2 [5]) nonlinearity, an attenuator has been provided which attenuates both ranges of the dialed voltage by a factor of 100. This precision resistive attenuator has a 50 Ω output impedance and is inserted between the buffer amplifier output and the CAL OUT terminals when the attenuator switch is in the "÷100" position. When calibrator voltages larger than 50 mV are desired, this switch should be in the OUT position. If required, calibration of the ÷100 attenuator should immediately follow the preceding calibrations. The calibrator control positions are not changed, except for putting the attenuator in the ÷100 position. The laboratory K-V divider input is connected to the laboratory reference and set to the ratio of 0.05 V to the standard cell voltage (approx. .0491090). The ÷100 pot is then adjusted so that the calibrator voltage equals the K-V divider output voltage.

The uncertainty in transferring the standard cell voltage to the laboratory voltage reference at the 1.01815 V level is less than ±2 ppm. The uncertainties in stepping the reference voltage down to 1.000000 V (calibration of dc reference) and up to 5.000000 V are 4 and 10 ppm, respectively. These uncertainties are caused mostly by varying thermal voltages at connectors, circuit noise, and lack of resolution in adjustments. The 10 ppm uncertainty includes 1 ppm systematic error, caused by the nonlinearity of the laboratory K-V divider. The measured temperature coefficients of the dc reference and buffer amplifier (on X10 range) are -6 ppm/°C and +2 ppm/°C, respectively. The corresponding imprecisions for a 2°C range are ±12 ppm and ±4 ppm.

The expected maximum temperature coefficient for the attenuator is ±3 ppm/°C (±6 ppm uncertainty for a 2°C range). Tests show that thermal voltages up to ±0.7 μV are generated at the CAL OUT terminals when the voltage applied to the ÷100 attenuator is zero. This corresponds to ±14 ppm of the 50 mV output from the attenuator when it is being calibrated. Also, the nonlinearity of the laboratory K-V divider at the .0491090 setting may contribute 2 or 3 ppm error to the calibration of the attenuator. Finally, the adjustment of the attenuator has an uncertainty of about 2 ppm. Therefore, a systematic error of 3 ppm (from K-V divider) and an imprecision of 22 ppm have been assigned to the ÷100 attenuator calibration.

Based on a linearity comparison with the laboratory K-V divider, the K-V divider employed in the calibrator can cause up to 25 ppm error in the ac calibrator voltage (V_C). It is planned to check this unit against the laboratory standard approximately once a year.

Control charts (fig. 5) will be kept which show the changes in the ac and dc reference voltages and the buffer amplifier gain that occur between calibrations. Based on measurements and manufacturer's specifications, the yearly drift rates of the standard cell, ÷100 attenuator, and the K-V divider are expected to be less than 2, 2, and 3 ppm, respectively. Since these systematic errors are very small compared with the expected uncertainty of the ac calibrator voltage, no control charts are planned for these components.

3.4 AC-DC Difference Calibration of RMS/DC Converter

The ac-dc difference of the rms/dc converter used in the rms voltmeter was calibrated at NBS in April 1981. The reference thermal voltage converter (TVC), employed in the calibration test set, consisted of model FE reference thermal element and model F.10V (#1) multiplier range resistor. This thermal element, consisting of four single junction thermal elements in series, was designed to have negligible ac-dc difference for frequencies down to 10 Hz or below. Ten comparisons were made between the rms/dc converter and reference TVC involving four measurements each (ac, dc, dc reverse, ac), yielding an average ac-dc difference of ±0.25 ppm. The standard deviation of a comparison was 5.83 ppm, so that the standard error of the mean was 1.84 ppm. If the selected confidence level is 0.99, Student's t is 3.3 and the imprecision in the calculated ac-dc difference is ±6 ppm.

The only known source of systematic error in the ac-dc calibration is the uncertainty in the ac-dc difference of the reference TVC. This unit has been intercompared with several other reference TVCs, with an ac-dc difference of less than 1 ppm [6]. These units are maintained at NBS and are believed to have zero ac-dc difference to within 1 or 2 ppm for frequencies as low as 10 Hz. If ±2 ppm uncertainty is allowed for the reference TVC, the estimated ac-dc difference of the rms/dc converter is 0 ±8 ppm.

It is recommended that multi-junction thermal converters (MJTCs) be re-calibrated every five years. This re-calibration interval should also apply to the rms/dc converter, since its ac-dc difference is determined by the ac-dc difference of the MJTC employed.

3.5 Summary of Calibration Errors of AC Voltage Calibrator

Table 3 lists the estimated uncertainties which limit the calibration accuracy of the ac calibrator. Item 9 of this table 3 shows that, following a frequency response calibration, the (V_f-V_{10} = 0) with an uncertainty of ±20 ppm. It should be emphasized

Table 3. Estimated systematic error and imprecision components of the uncertainties which limit calibration accuracy of ac voltage calibrator. Estimated components of uncertainties less than 0.5 ppm are rounded to zero.

		Systematic error	Imprecision
(1)	Standard cell uncertainty	2 ppm	0 ppm
(2)	Standard cell lab reference transfer	0	2
(3)	Step-down to 1 V level in dc reference	0	4
(4)	Step-up to 5 V level in dc calibrator	1	9
(5)	Temperature coefficient of dc reference (-6 ppm/°C) for a 2°C range	0	12
(6)	AC/DC comparisons (calibration of ac calibrator at 10 Hz)	20	12
(7)	AC-DC difference uncertainty of rms/dc converter	2	6
(8)	Temperature coefficient of ac reference (+3 ppm/°C) for a 2°C range	0	6
(9)	Calibration of (V_f-V_{10})	10	10
(10)	Maximum error from calibrator K-V divider	25	0
(11)	Maximum K-V drift between calibrations	3	0
(12)	Temperature coefficient of buffer amplifier on X10 range (+2 ppm/°C) for a 2°C range	0	4
(13)	Calibration of the ÷100 attenuator	3	22
(14)	Maximum attenuator drift between calibrations	2	0
	Sub-totals	68	33 (rss)

Total uncertainty of ac calibrator voltage V_c	±101 ppm

that when frequency response calibrations are made of a customer's voltage source or voltmeter, only the uncertainty of (V_f-V_{10}) needs to be known. Table 3 also shows that the estimated uncertainty of the ac calibrator voltage V_c is ±101 ppm, following a complete calibration of the dc and ac calibrator circuits.

Although periodic calibration intervals cannot be established for these circuits until control chart data are available, it is believed that a specified maximum uncertainty of ±200 ppm for the ac calibrator will allow calibration intervals approaching one year for the dc reference voltage, buffer amplifier gain, and (V_f-V_{10}). A somewhat shorter calibration interval is expected for the ac reference. The corresponding error budget for (V_f-V_{10}) alone is ±35 ppm. Therefore, the calibration intervals will be chosen to ensure that the maximum uncertainties of (V_f-V_{10}) and V_c are less than ±35 ppm and ±200 ppm (0.020%), respectively.

Although considerable reliance will be placed on control chart data to anticipate future drifts in calibrator circuits, accurate checks on circuit performance can be made at any time using shortened procedures. Using only one set of measurements as shown in table 1 to determine (V_f-V_{10}), instead of the average of two sets, decreases the measurement time from 48 minutes to 24 minutes. The imprecision increases from ±10 ppm to ±14 ppm and the allowable value of (V_f-V_{10}) should be increased from ±10 ppm to ±14 ppm before being readjusted. Using one set of measurements as shown in table 2 to determine $(V_{ac}-V_{dc})$, instead of the average of three sets, decreases the measurement time from 36 minutes to 12 minutes. The imprecision increases from ±12 ppm to ±21 ppm and the allowable value of $(V_{ac}-V_{dc})$ should be increased from ±20 ppm to ±35 ppm before being readjusted. Substituting these values into table 3 (items 6 and 9) yields maximum uncertainties of ±28 ppm and ±125 ppm for (V_f-V_{10}) and V_c, respectively. The time required to calibrate the dc reference, buffer amplifier gain, and ÷100 attenuator is 13 minutes. (These procedures cannot be shortened.) Therefore, the total calibration time of the dc and ac calibrators, using the shortened procedures, is approximately 50 minutes.

3.6 Frequency Response of the RMS Voltmeter

The ac calibrator can be used to calibrate voltage standards at frequencies other than the nominal calibrator frequencies, if the frequency response of the rms voltmeter (DVM) is known. The response of the DVM decreases as the frequency of the input signal is decreased below ~2 Hz, because of increasing ripple voltage in the rms/dc converter and lack of square law response by the MJTC of this circuit [2]. The effect from ripple is minimized, however, by the HEAVY FILTERING circuit which is used for most calibration work (see sec. 3.1.1). Five (V_f-V_{10}) comparisons were made using the ac calibrator voltage as the input signal. The mean values of these comparisons and the standard deviation of a comparison for each frequency are shown in table 4.

Table 4. Frequency response of the rms voltmeter with corrections applied for variations in the ac calibrator voltage, used for the input signal. The mean values and standard deviation, s_f, were obtained from five (V_f-V_{10}) DVM comparisons.

Frequency (f)	$\overline{(V_f-V_{10})}_{DVM}$	s_f
5 Hz	0 ppm	6.1 ppm
2	-2	6.5
1	-13	4.5
0.5	-49	6.5
0.2	-109	5.5
0.1	-208	2.7

The voltmeter response as a function of input signal frequency can be approximated by second degree equations of curves that pass through the values of $\overline{(V_f-V_{10})}_{DVM}$ at frequencies of 2, 1, 0.5 Hz and at 0.5, 0.2, and 0.1 Hz. The equation that is applicable to the 0.5 to 2 Hz range is

$$(V_f-V_{10})_{DVM} = -105.33 + 133.00f - 40.67f^2. \qquad (1)$$

The equation for the 0.5 to 0.1 Hz range is

$$(V_f-V_{10})_{DVM} = -346.50 + 1582.50f - 1975.00f^2. \qquad (2)$$

These equations are used to plot the curves in figure 6.

As indicated previously, the lack of flatness in the DVM response is attributed to the rms/dc converter response. Since applying corrections from the curves in figure 6 or the preceding equations is quite tedius, an effort was made to improve the DVM frequency response sufficiently so that corrections usually are not necessary. This was accomplished by employing frequency-dependent negative feedback circuits in a section of the input amplifier, as shown in figure 7. With these circuits, the amplifier response approximately complements the rms/dc converter response. Components R1, C1, and R2, C2 provide

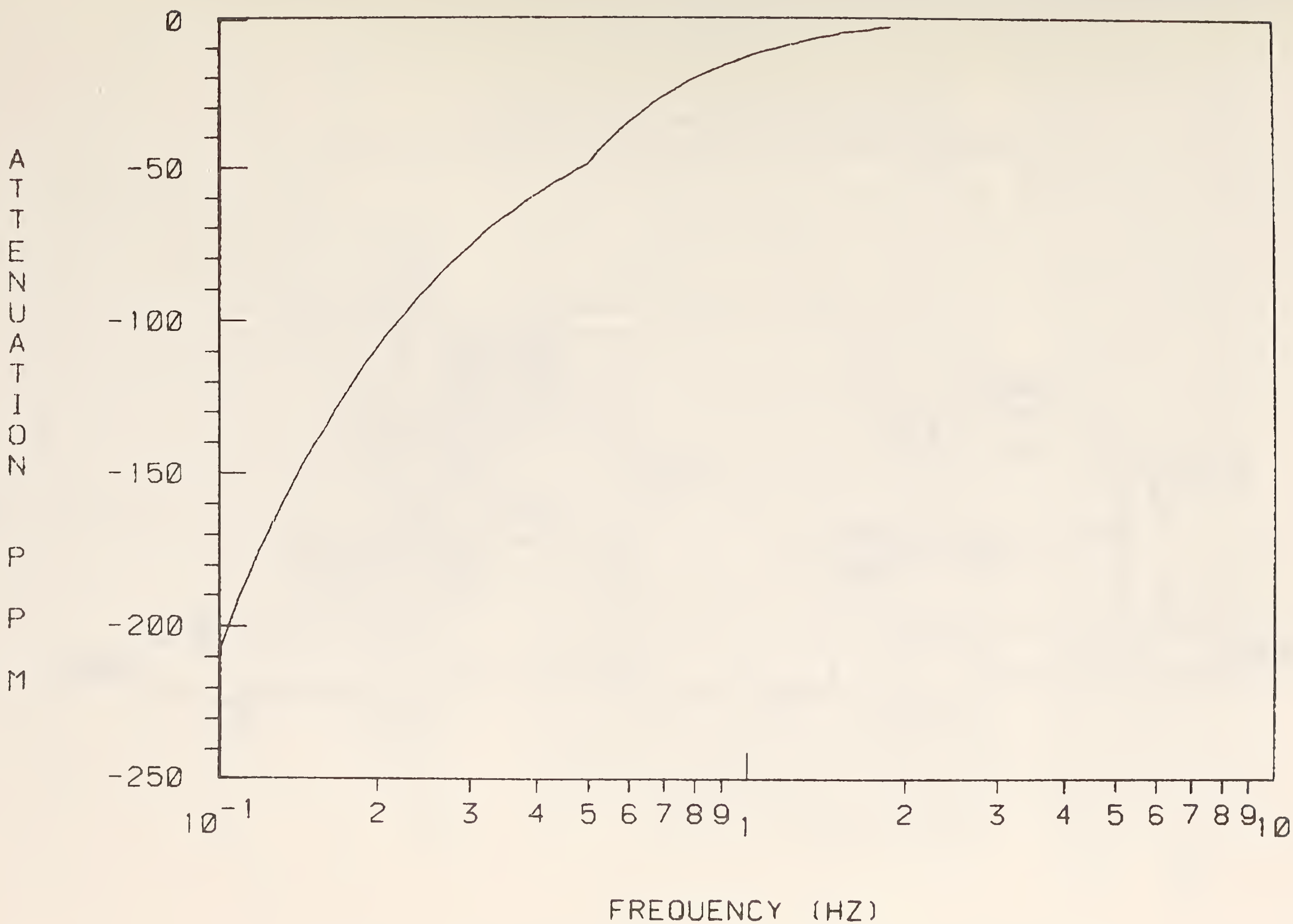

Figure 6. Plot of DVM frequency response, using equations 1 and 2.

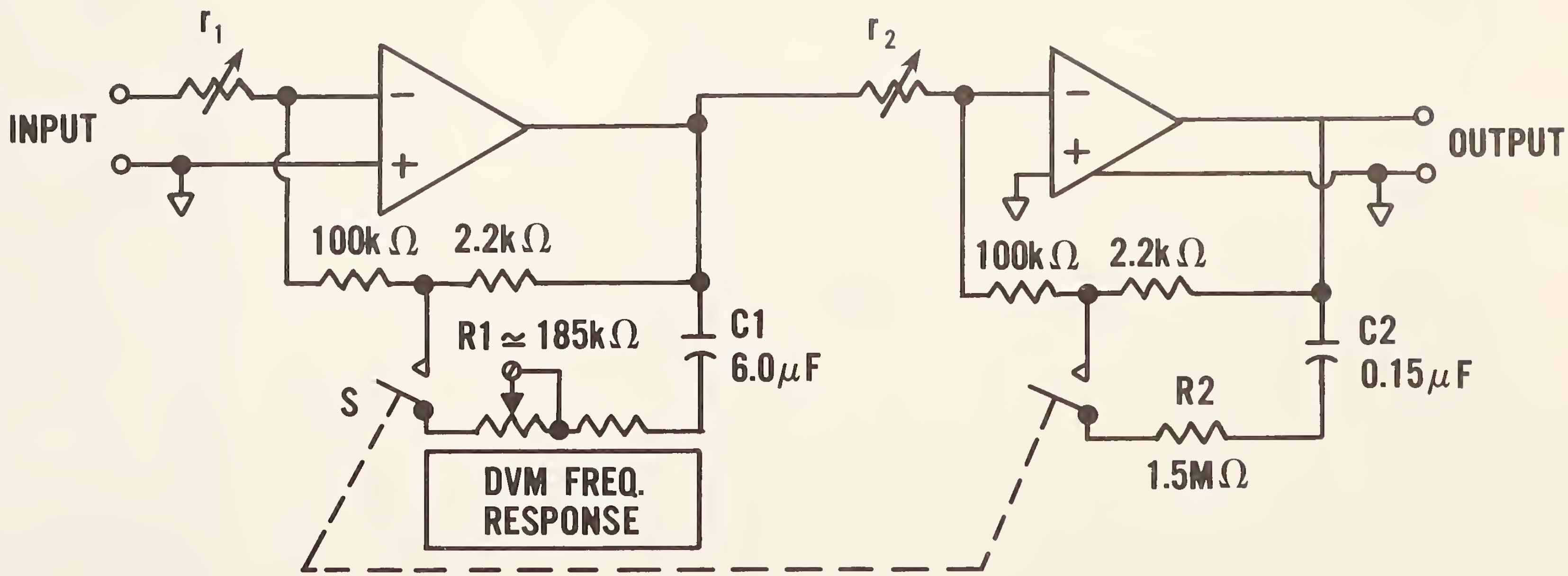

Figure 7. Section of input amplifier used to compensate for decrease in DVM response at low frequencies.

high-frequency attenuations of approximately 250 and 30 ppm, respectively. The corresponding corner frequencies are 0.14 and 0.71 Hz. The frequency response of the circuit which has the higher attenuation is adjustable over a small range by the DVM FREQ RESPONSE pot. Figure 8 is a plot of the amplifier transfer characteristic with the DVM FREQ RESPONSE circuit switched in (switch S closed). Resistances r_1 and r_2 were arbitrarily assigned the value of 100 kΩ; however, measurements show that the frequency response is essentially independent of the values of r_1 and r_2 selected by the V-RANGE-MV switch (see fig. 2).

The frequency response of the circuit shown in figure 7 was combined with the responses of eqs. 1 and 2 and plotted in figure 9. This response curve shows that the maximum values of $(V_f-V_{10})_{DVM}$ occur at 0.5 Hz and approximately 0.14 Hz. A good estimate of the outside limits of $(V_f-V_{10})_{DVM}$ can be obtained by measuring this quantity at 0.1, 0.2, and 0.5 Hz, using the ac calibrator. Table 5 shows the DVM response at the lowest four calibrator frequencies, obtained from 13 measurements. Corrections were made for the measured frequency response of the calibrator (systematic error), leaving only the imprecision of these measurements (±6.0 ppm) as the uncertainty of the calibrator voltages. (The frequency response and estimated standard deviation of the ac calibrator were based on 5 and 13 measurements, respectively - see section 3.1.1.) Using the maximum estimated standard deviation of the measurement process represented by table 5 (6.4 ppm) and a confidence level of 0.99, the imprecision of these measurements is 5.4 ppm. Combining this imprecision with the calibrator imprecision gives ±8.1 ppm as the maximum uncertainty of $(V_f-V_{10})_{DVM}$. Therefore, the outside limits of $(V_f-V_{10})_{DVM}$, measured at 0.1, 0.2, 0.5, and 1 Hz, are approximately +20 and -19 ppm.

Table 5. Measured DVM frequency response with input amplifier compensated. The average values of $(V_f-V_{10})_{DVM}$ and estimated standard deviations, s_f, are based on 13 measurements.

Frequency (f)	$(\overline{V_f-V_{10}})_{DVM}$	s_f
1 Hz	+1 ppm	3.0 ppm
0.5	-11	4.2
0.2	+12	6.4
0.1	-7	5.0

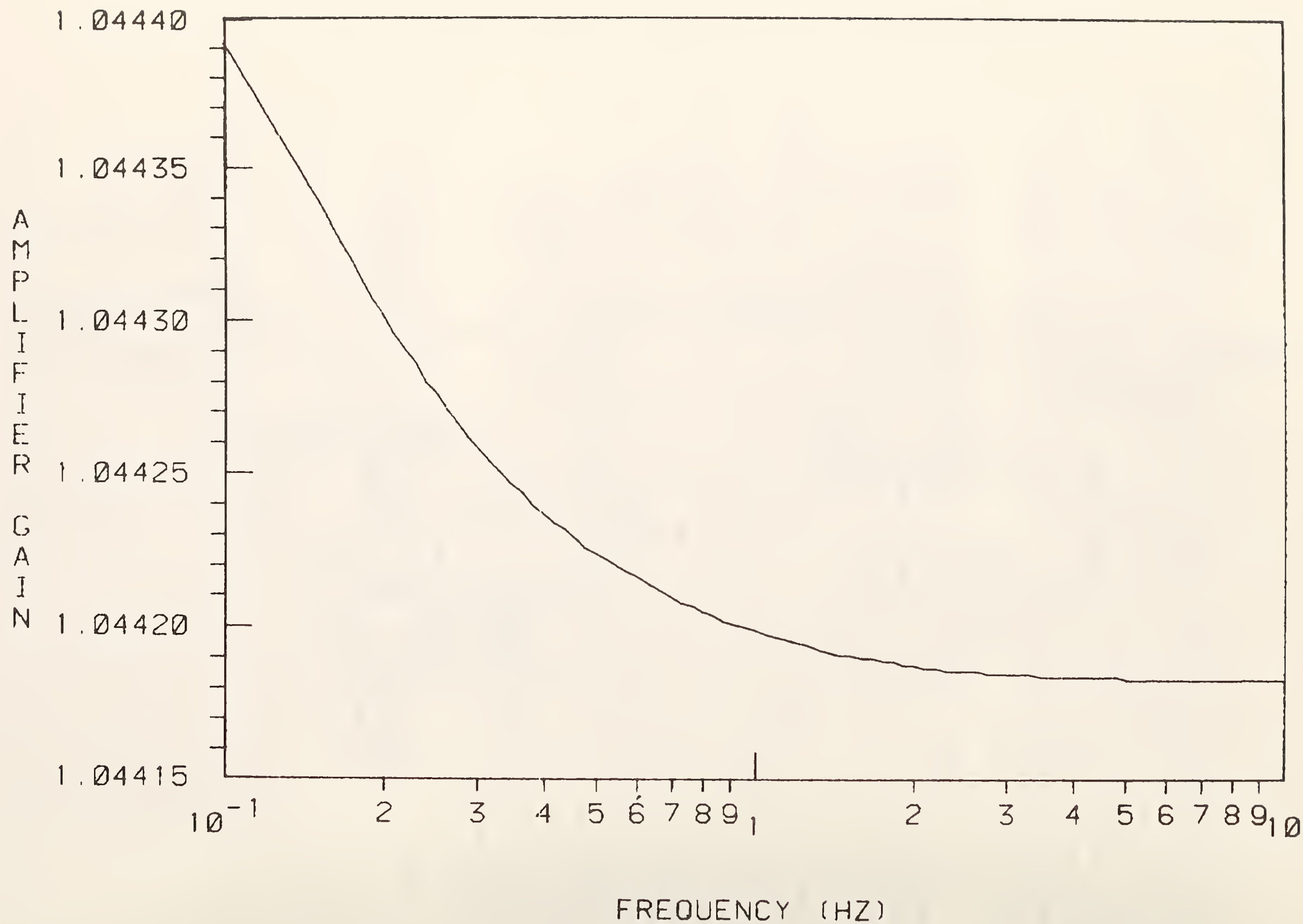

Figure 8. Transfer characteristic of input amplifier with DVM FREQ RESPONSE circuit switched in (see fig. 7).

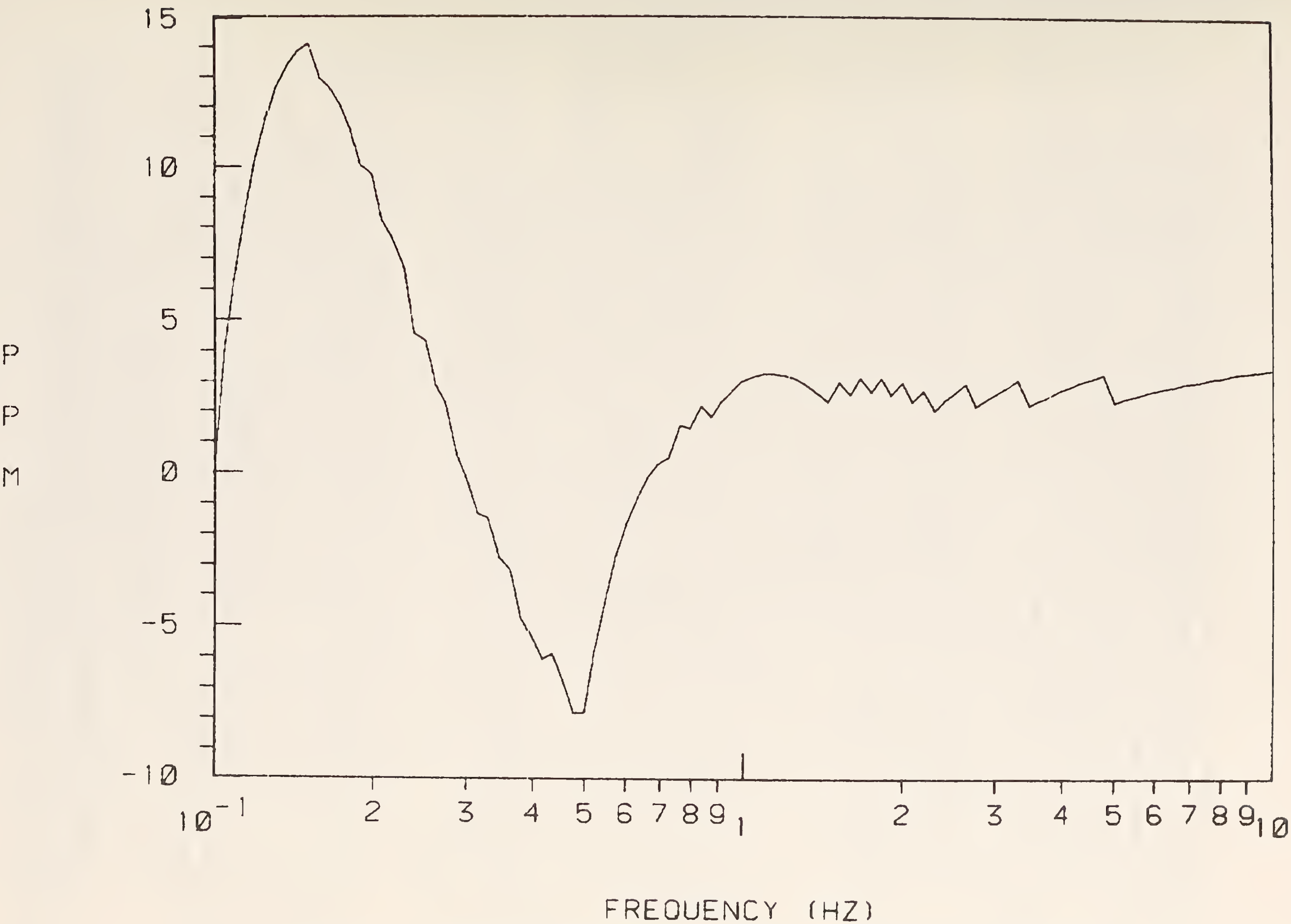

Figure 9. Theoretical DVM response with input amplifier frequency compensated.

These limits result from using 5 and 13 measurements to establish the frequency response of the calibrator and DVM, respectively. For routine calibrations of the DVM frequency response, it is planned to use three measurements. Assuming that the calibrator response is also obtained from three measurements, the DVM and calibrator imprecisions will be 11.3 and 7.8 ppm, respectively. Combining these quantities gives 13.7 ppm, an increase of 5.6 ppm over the imprecision applicable to the frequency response values in table 5. To obtain the maximum expected values of $(V_f-V_{10})_{DVM}$, using three DVM and three calibrator measurements, the maximum frequency response values in figure 5 should be increased by 5.6 ppm, yielding +17.6 and -16.6 ppm. Adding the corresponding imprecision to these quantities gives estimated uncertainty limits of +31.3 and -30.3 ppm to $(V_f-V_{10})_{DVM}$. The response curve in figure 9 indicates that $(V_f-V_{10})_{DVM}$ is approximately 4 ppm larger at 0.14 Hz than at 0.2 Hz. Also, any uncertainty in the difference between $(V_{.14}-V_{10})_{DVM}$ and $(V_{.2}-V_{10})_{DVM}$ in figure 6 carries over to figure 9. The computed value of this difference is approximately 55 ppm. It is believed that the uncertainty in this difference should not exceed 10 percent or 6 ppm. Adding this uncertainty and the 4 ppm difference mentioned above to the uncertainty limits for the measured frequency response yields +41.3 and -30.3 ppm as the uncertainty limits of $(V_f-V_{10})_{DVM}$ for any frequency. Since the attenuation caused by the feedback circuits of the input amplifier is small at 0.1 Hz but increases with frequency, the DVM response curve (fig. 9) can be effectively rotated about the 0.1 Hz point of the curve by adjusting the DVM FREQ RESPONSE pot. Therefore, this control can be used to adjust the +41.3 and -30.3 limits to approximately ±36 ppm. Drift in $(V_f-V_{10})_{DVM}$ that cannot be removed by adjusting the DVM FREQ RESPONSE pot, estimated to be less than 2 ppm in five years, can be compensated by trimming the values of R2 and C2 in figure 7. However, to obviate the trimming, the frequency response will be specified as 0 ±40 ppm to allow some margin for drift of this type.

It is useful to estimate the uncertainty that the DVM response causes if two voltages are compared which have frequencies differing by no more than 5 percent. Figure 9 shows that the maximum rate of change of $(V_f-V_{10})_{DVM}$ with frequency occurs over the frequency range of 0.1 Hz to 0.14 Hz, approximately. Assuming that $(V_f-V_{10})_{DVM}$ changes by no more than two-thirds of the specified limits of ±40 ppm over this frequency range (a 40% change in frequency), a 5 percent uncertainty in frequency corresponds to a maximum uncertainty in $(V_f-V_{10})_{DVM}$ of approximately ±7 ppm.

4. CALIBRATIONS OF VOLTMETERS

Calibrations are performed on rms-responding ac voltmeters using the ac voltage calibrator of the NBS AC Voltmeter/Calibrator. AC voltmeters can be calibrated at frequencies of 10, 5, 2, 1, 0.5, 0.2, and 0.1 Hz at any voltage level between 0.5 mV and 7 V.

The total uncertainty of a calibration is $\pm(\varepsilon_c + \varepsilon_r)$, where ε_c is the uncertainty of the ac voltage calibrator voltage and ε_r is the imprecision of the calibration process. The estimated uncertainty of the ac voltage calibrator is ±0.020 percent, as described in section 3.5. The imprecision for a given calibration point is $ts/\sqrt{N}$, where t is Student's t for the selected confidence level, s is the standard deviation for a measurement, and N is the number of measurements (test runs) used to obtain the mean values of the measured quantities (voltmeter readings).

Unless otherwise requested by the customer, a single accuracy of calibration will be given for the corrections to the calibration points, based on a confidence level of 0.98 and the largest standard deviation encountered. It is expected that the value of N, requested by the customer, will generally be 3, 4, or 5. Assuming a selected confidence level of 0.98, values of t corresponding to N equal 3, 4, and 5 are approximately 7.0, 4.5, and 3.7, respectively.

5. CALIBRATIONS OF VOLTAGE STANDARDS

Voltage calibrations are performed on precision ac sources using the ac voltage calibrator and rms voltmeter of the NBS Voltmeter/Calibrator. The rms voltmeter is used as a transfer voltmeter to compare the voltages (of the same nominal level) from the test unit and the ac calibrator. Voltage calibrations can be made at any frequency in the 10 Hz to 0.1 Hz range and are usually made near the full-scale level of the DVM ranges (2, 5, 10, 20, 50 mV, and 0.1, 0.2, 0.5, 1, 2, 5 V).

If the voltage standard is of a design which has inherently stable voltage with respect to frequency, a frequency response (relative voltage) calibration may be preferable to a conventional voltage calibration. The user then establishes the voltage levels by calibrating the voltage at 10 Hz. Since the rms voltmeter has a frequency response that is flat to within ±40 ppm, it is used to determine the frequency response of voltage sources. Frequency response calibrations can be made at any frequency in the 10 Hz to 0.1 Hz range and are usually made near the full-scale level of the DVM ranges (2, 5, 10, 20, 50 mV, and 0.1, 0.2, 0.5, 1, 2, 5, 10 V).

5.1 Voltage Calibrations

For each calibration point, the rms voltmeter (DVM) is used to compare the voltage V_T from the standard under test with the voltage V_C of the same nominal level from the ac voltage calibrator, choosing the calibrator frequency closest to that of the voltage being measured. After the test runs are made, the average $\overline{(V_C - V_T)}$ is formed for each calibration point, yielding corrections to the nominal voltage values of the test unit.

If the uncertainty of the calibrator voltage and the uncertainty caused by the DVM frequency response are denoted by ε_c and ε_m, respectively, the total uncertainty of a calibration point is given by $\pm(\varepsilon_c + \varepsilon_m + ts/\sqrt{N})$, where s is the standard deviation of a $(V_c - V_T)$ comparison and N is the number of comparisons (test runs). If the frequencies of the voltages being compared are within 5 percent of each other, ε_m is ±7 ppm. If the frequency difference is larger, the worst case value of ε_m, ±40 ppm, is used. The value assigned to ε_c is ±200 ppm (±0.02%); however, if the highest calibration accuracy is required by the customer, ε_c can be decreased to ±125 ppm by a special calibration of the NBS instrument.

Unless otherwise requested by the customer, a single accuracy of calibration will be given for the corrections to the calibration points, based on a confidence level of 0.98 and the largest standard deviation encountered. It is expected that the value of N, requested by the customer, will be 3, 4, or 5.

5.2 Frequency Response Calibrations

These calibrations are made using the DVM to compare test unit voltages of frequency f with the 10 Hz value. After N comparisons, the quantities $\overline{(V_f - V_{10})}$ are computed for each test frequency, yielding the frequency response. The uncertainty of these calibration points is $\pm(\varepsilon_m + ts/\sqrt{N})$, where ε_m is ±40 ppm, the frequency response of the DVM, and s is the standard deviation of a comparison.

Unless otherwise requested by the customer, a single accuracy of calibration will be given for the frequency response, based on a confidence level of 0.98 and the largest standard deviation encountered. It is expected that the value of N, requested by the customer, will be 3, 4, or 5.

6. ACKNOWLEDGMENTS

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NBS Provides Voltage Calibration Service in 0.1–10-Hz Range Using AC Voltmeter/Calibrator

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Abstract—**Prompted by the need to support vibration and pressure measurements at frequencies down to 0.5 Hz (with expected future needs to 0.1 Hz), NBS now offers a calibration service for voltage standards and rms voltmeters in the range of 0.1–10 Hz. The means for the service is an "ac Voltmeter/Calibrator," an NBS-developed instrument containing an rms digital voltmeter and ac and dc voltage calibrators. The methods used to calibrate the ac voltage calibrator are discussed; also, application of the ac Voltmeter/Calibrator to the calibration of customers' voltage and voltmeter standards is described. Finally, a multifrequency voltage reference source with frequency-independent amplitude is proposed as a more suitable transfer standard than thermal voltage converters (TVC's) for the 0.1–10-Hz range.**

I. Introduction

THE National Bureau of Standards (NBS) supports ac voltage measurements in standards laboratories by calibrating the ac–dc difference of thermal voltage converter (TVC) reference standards.[1] TVC working standards, calibrated from the reference standards, are then used to transfer the accuracy of dc voltage standards to ac voltage standards and ac voltmeters. NBS routinely calibrates TVC's from the megahertz region down to 20 Hz. In special cases, calibrations have been made down to 5 Hz and a few times down to 2 Hz. Voltage measurement support is now required at still lower frequencies. Vibration and pressure measurements used in the test of land, sea, air, and space vehicles as well as in other applications now require the measurement of output voltages from vibration and pressure transducers at frequencies down to 0.5 Hz, with expected future requirements as low as 0.1 Hz.

Theoretical and practical limitations arise in calibrating TVC's, and employing them to make calibrations, at the lower infrasonic frequencies. Below ~2 Hz, significant cyclic temperature variation of the TC heater occurs. This improper integration, indicated by ripple in the output voltage, presents the following measurement problems.

1) Large ripple filter time constants are required to reduce fluctuations to an acceptable level in the indicating instrument (galvanometer, digital voltmeter (DVM), etc.), causing slow tedious measurements. 2) The ac–dc difference of the TVC increases as the square of the output ripple before external filtering is applied, because of its lack of square-law response [2]. Thus below 2 Hz, the ac–dc difference can be significant and must be determined at a number of frequencies.

Since TVC calibrations below 2 Hz are slow and costly, it appears that a precision sine-wave voltage source with nominally equal outputs at several discrete frequencies in the 0.1–10-Hz range is a more appropriate transfer standard than a TVC for this frequency range. If the variation in rms voltage level with frequency of the voltage standard is known from a calibration, the absolute voltage at each frequency can then be established by calibrating the sine-wave standard at 10 Hz using a dc voltage standard and conventional TVC transfer circuits.[2]

NBS proposes to support voltage measurements in the 0.1–10-Hz range primarily by accurately determining the rms frequency response of single-voltage-level sine-wave voltage standards such as described above. However, calibration of multirange sine-wave voltage standards and rms voltmeters is also offered. The equipment for making these calibrations is described in the following sections.

II. Voltage Calibration Methods for 0.1–10-Hz Range

A. Description of NBS AC Voltmeter/Calibrator

The means for calibrating voltage standards and rms voltmeters in the 0.1–10-Hz range is an rms digital voltmeter/calibrator (Fig. 1) described in an earlier paper [2]. A brief discussion of the circuit (Fig. 2) will be given here to describe its application to calibrations. The voltage calibrator shown in the lower part of the figure can function as either a dc or ac calibrator. It basically consists of a 7-digit Kelvin–Varley (K–V) divider fed by a reference voltage of 1 V (sine wave, +dc, or −dc) and buffered at its output by a voltage follower with selectable gains of 1 or 10. The sine-wave reference is shown in Fig. 3. The sine wave is synthesized by a 7-bit counter READ-ONLY memory (ROM) digital-to-analog converter (DAC) circuit so that 128 input pulses are required per sine-wave cycle. The necessary input

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[1] Thermal converters (TC's) and thermal voltage converters (TVC's) are described in [1]. The reference also includes an extensive bibliography on ac–dc comparators for LF measurements.

[2] An rms voltmeter with small ac–dc difference at 10 Hz may be used instead of the TVC circuits.

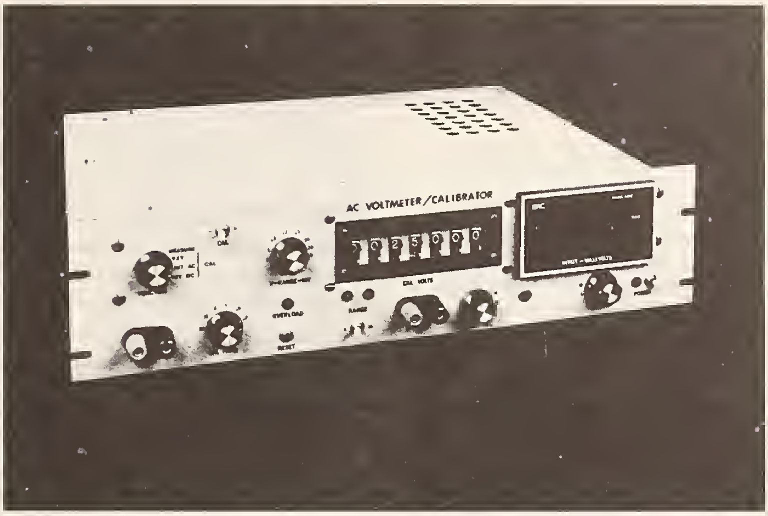


Fig. 1. AC Voltmeter/Calibrator. The rms voltmeter and voltage calibrator operate at dc and over the 0.1–50-Hz range.

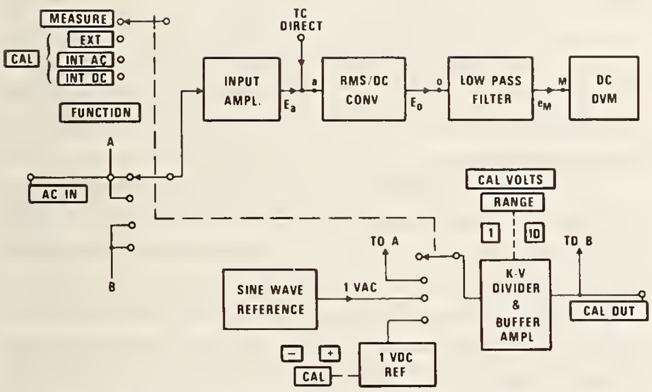


Fig. 2. Simplified block diagram of ac Voltmeter/Calibrator. Instrument contains an rms digital voltmeter and ac and dc voltage calibrators.

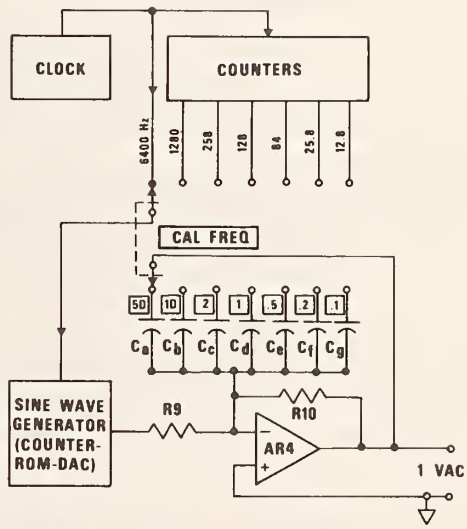


Fig. 3. Sine-wave reference used in the calibrator.

frequencies to the circuit are obtained using a fixed clock frequency and scaling it to obtain output frequencies of 0.1, 0.2, 0.5, 1.0, 2.0, 10, and 50 Hz. The amplifier is designed to have an output of 1-V rms and sufficient filtering to reduce the contribution to the rms value of the output of all harmonics generated by the DAC to a few parts per million (ppm). The ac calibration voltages, available at the CAL OUT terminal (Fig. 2), are applied to the voltmeter input when the FUNCTION switch is in the CAL INT AC position. The CAL INT DC position selects dc calibration voltages. The dc calibrator serves as the basic reference for the AC Voltmeter/Calibrator. Calibration of the dc and ac calibrators and their resulting accuracies are discussed in Section III.

The rms digital voltmeter, shown functionally in the upper part of Fig. 2, was designed to serve three measurement functions: 1) direct rms measurement of voltages, 2) ac–dc transfer measurements so that the dc calibrator can be employed to calibrate the ac calibrator, and 3) ac–ac transfer measurements so that ac voltage sources can be calibrated using the ac calibrator. The accuracy with which these measurements can be made largely depends upon the rms–dc converter design and the methods used to filter ripple in the converter and succeeding circuits. The ripple in the converter's output voltage E_0 is filtered by the low-pass filter and dc DVM, a voltmeter with integration periods of 1 and 10 s. Use of these integration periods yields voltmeter resolutions of 4 and 5 digits, respectively, and makes it possible to obtain perfect filtering (zero fluctuations of the indicated voltage) at all calibration frequencies. The importance of these characteristics in making very accurate ac–dc and ac–ac transfer measurements is discussed in the Appendix.

The rms voltmeter employs a multijunction thermal converter (MJTC) as the sensing element in its rms–dc converter. It is shown in [2] that the converter and, therefore, the voltmeter have true rms response. Selection of an MJTC with small deviation from square law response resulted in an rms voltmeter with an ac–dc difference of about 10 ppm at 1

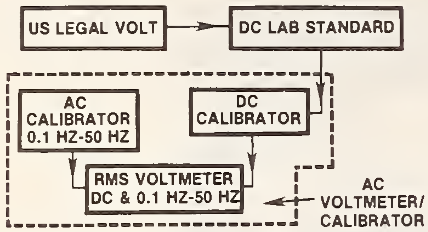


Fig. 4. Calibration of the ac calibrator in the ac Voltmeter/Calibrator. After calibration against the dc lab standard, the dc calibrator is employed to calibrate the ac calibrator, using the rms voltmeter as a transfer instrument.

Hz, decreasing to ~ 0 ppm at 10 Hz. The ac–dc difference increases below 1 Hz and is ~500 ppm at 0.1 Hz. Thus accurate ac–dc comparisons, such as are used in calibrating the ac calibrator, are limited to frequencies in the 1–10-Hz range. However, accurate ac–ac comparisons are feasible down to 0.1 Hz if the voltages being compared have approximately the same frequency.

B. Calibration of AC Voltmeters and Voltage Standards

The ac calibrator may be used to calibrate ac voltmeters at any of the above-mentioned frequencies for voltage levels ranging from 0.2-mV to 7-V rms.

The rms voltmeter accuracy ranges from 0.1–0.2 percent of reading, depending upon frequency and voltage level, and is not sufficient to calibrate ac voltage standards. On the other hand, when the voltmeter used as a transfer instrument and ac calibrator are employed to make ac–ac transfer measurements, measurement accuracy is limited only by the calibrator accuracy and voltmeter resolution. For example, if $e_i(t)$, a voltage to be measured, is applied to the rms voltmeter, its correct rms value E_i is

$$E_i = E_i'(1 - \varepsilon) \tag{1}$$

(or, $E_i' \simeq E_i(1 + \varepsilon)$), where E_i' is the voltmeter reading and ε is the voltmeter error in proportional parts. If E_i' is dialed into the calibrator, the voltmeter reading is, approximately,

$$E_c' \simeq E_i'(1 + \varepsilon). \tag{2}$$

Solving for E_i from (1) and (2) gives

$$E_i \simeq 2E_i' - E_c'. \tag{3}$$

AC voltage standards may be calibrated at any frequency from 0.1 to 10 Hz over the voltage range of 0.2-mV–7-V rms.

III. Calibration of the AC Voltmeter/Calibrator

The dc calibrator is calibrated against laboratory standards as shown in Fig. 4. Calibrations are made at the 1-V and 5-V levels to set the voltage level of the 1-V dc reference and the gain of the buffer amplifier on the × 10 range (see Fig. 2). The resulting dc calibrator accuracy at 23 ± 1°C is ± 50 ppm, based on the average of both polarities.

As mentioned previously, the ac calibrator voltages may be accurately measured at any frequency in the 1–10-Hz range, using the rms voltmeter to compare ac and dc calibrator voltages. Calibration of the ac calibrator is performed at 10 Hz and consists of adjusting the ac reference so that the ac and dc calibrator voltages are equal at the 5-V level. Following calibration, the uncertainty of the calibrator voltage at 10 Hz is ± 90 ppm and consists of the dc calibrator uncertainty plus twice the voltmeter resolution. The uncertainty of the ac calibrator voltage at the other frequencies is somewhat larger than ± 90 ppm because the calibrator amplitude varies slightly with frequency. A conservative figure for the overall calibrator uncertainty may be obtained by adding the amplitude variation over the 0.1–10-Hz frequency range to the calibrator voltage uncertainty at 10 Hz. The estimated amplitude variation, based on measurements described in the Appendix, is 61 ppm. Adding this quantity to the calibrator accuracy at 10 Hz, and including the measured temperature coefficient of the ac calibrator (± 50 ppm/°C), yields an overall ac calibrator accuracy of ± 0.02 percent at 23 ± 1°C.[3] Following calibration, the ac calibrator is then employed to adjust and calibrate the rms voltmeter.

IV. Equipment Needed for 0.1–10-Hz Voltage Calibrations

In general, the following equipment is needed in a standards laboratory for voltage calibrations in the 0.1–10-Hz frequency range.

1) A laboratory multirange dc voltage standard.

2) A TVC and associated equipment for ac–dc transfer measurements at or near 10 Hz. Item 5 may also be suitable for this purpose.

3) A single voltage level, multifrequency[4] sine-wave voltage standard, whose amplitude variation with frequency (frequency response) is calibrated and has excellent long-term stability. This unit serves as a voltage transfer standard.

4) A multifrequency multirange sine-wave standard.

5) An rms transfer voltmeter with good short-term stability, including periodic fluctuations, and sufficient resolution to make accurate ac–ac voltage comparisons. The voltages being compared must be of approximately the same frequency, unless the frequency response is accurately known. Good voltmeter accuracy is not required since only small voltage differences will be measured; however, the differential nonlinearity must be small.

6) A calibrated resistive voltage divider, whose ratios are frequency-independent up to at least 10 Hz (e.g., a low impedance K-V divider).

Items 1 and 2 serve to calibrate the voltage level of item 3. Item 6 is then used to step the voltage of item 3 up or down, as required, to the nominal value of the voltage being calibrated in item 4. Item 5 is used for the ac–ac comparison and calibration. After calibration, the multirange sine-wave standard is then the means for calibrating rms voltmeters.[5] If items 1, 3, 4, and 6 are not already available as separate

[3] For calibrator voltages below 2 mV, the accuracy decreases with decreasing voltage to 0.2 percent at 0.2 mV.

[4] The following discrete frequencies are desired: 0.1, 0.2, 0.5, 1.0, 2.0 5.0, and 10 Hz.

[5] NBS has also developed a sampling voltmeter for frequencies down to 0.1 Hz [3].

entities, they may be quite easily and economically combined into one circuit as shown in the lower part of Fig. 2.

As mentioned previously, NBS proposes to support voltage measurements in the 0.1–10-Hz range primarily by performing the calibration on item 3; however, calibration of multirange sine-wave voltage standards[6] and rms voltmeters is also being offered.

V. Proposed Voltage Transfer Standard for 0.1–10-Hz Range

A sine-wave generator based on the design of Fig. 3 is proposed as a voltage transfer standard for the 0.1–10-Hz range.[7] This circuit has the following characteristics, important for a sine-wave reference standard.

1) The calibrator voltage is nearly independent of the selected frequency. As indicated previously, the measured amplitude variation is approximately 60 ppm.

2) Temperature effects are essentially the same for all frequencies, if the temperature coefficients for the filter capacitors are approximately the same or quite small. The measured variation in amplitude temperature coefficients is < 2 ppm/°C over the 20–25°C range.[8]

3) Amplitude drift with time is nearly the same for all frequencies. The measured amplitude variation drifted approximately 8 ppm during 16 months of use.[9]

4) A small clock frequency drift has the same amplitude effect for all frequencies.

5) The phase and magnitude of the harmonics are essentially the same for all frequencies; therefore, average and peak-to-peak measures of amplitude variation versus frequency are good approximations, in fractional terms, to the rms differences.

6) Maximum drift of the dc output level with temperature change is primarily determined by the temperature coefficients of the DAC bipolar offset and the amplifier offset and is easily limited to 15 ppm/°C. This has a negligible effect on the rms value of the sine-wave output.

7) The circuit is easy and relatively inexpensive to implement.

8) Lower operating frequencies are feasible, should the need arise.

Appendix A
Effect of Voltmeter Resolution on Transfer Accuracy

The rms digital voltmeter's lack of resolution ("voltmeter resolution") contributes significantly to the uncertainty of a measurement. For example, if a 5-V signal is measured with 5-digit resolution (10-s integration period), voltmeter resolution contributes ± 20 ppm to the uncertainty of a single measurement or ± 40 ppm to an ac–ac transfer, involving two measurements. The same uncertainty also applies to an ac–dc comparison, since two measurements are effectively required—one ac measurement and the average of two dc measurements (one for each polarity). Fluctuations in the indicated voltage have the effect of further decreasing a voltmeter's resolution; therefore, careful filtering of the ripple generated in the rms–dc converter is necessary if the rms voltmeter is to be used for accurate transfer measurements.

If the rms voltmeter's integration period is denoted by T_i, perfect filtering of the ripple occurs for input frequencies of $f = n/2T_i$, where $n = 1, 2, 3, \cdots$, and includes all ac calibrator frequencies [2]. Minimum filtering occurs for $f = (n + \frac{1}{2})/2T_i$ and causes a worst case peak fluctuation in the indicated voltage of 0.05 percent at $f = 0.125$ Hz.

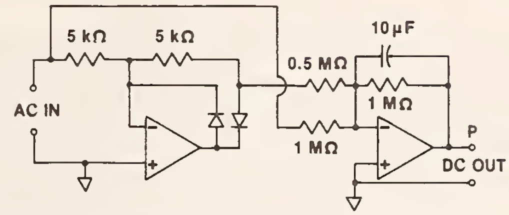


Fig. 5. Precision rectifier-filter circuit used to measure the average value of ac calibrator voltages.

Appendix B
Measurement of Calibrator Voltage Versus Frequency

As indicated in Section III, the variation of rms voltage level with frequency must be determined to establish the maximum uncertainty of the ac calibrator voltage. Since measurements using the rms voltmeter have insufficient accuracy at frequencies below ~ 1 Hz, the rms amplitude variation versus frequency was determined from a combination of peak-to-peak and average value measurements over the entire frequency range of 0.1–10 Hz and rms measurements over the 1–10-Hz range. Based on these measurements, the estimated rms amplitude variation is 61 ppm.

The method of making the peak-to-peak measurements is described in [2]. The average value of the ac voltage variation with frequency was measured using the precision rectifier-filter circuit shown in Fig. 5.[10] This circuit, an average-responding ac–dc converter, uses chopper-stabilized amplifiers and very stable passive components to insure good dc stability. In order to provide additional ripple filtering without increasing the response time unduly, the dc voltage output at node P was fed to node o of the ac voltmeter of Fig. 2 with the rms/dc converter disconnected and the readings taken from the dc DVM.

Basing differences between the rms values of voltages versus frequency on the differences between average values

[6] A calibration of amplitude variation with frequency for a given level within each voltage range is preferred over actual individual amplitude calibrations.

[7] An operating frequency of 5 Hz instead of 50 Hz is recommended and will be implemented in the NBS instrument. Also, a larger output voltage than 1 V should be considered. Voltage levels up to 7-V rms can be calibrated at NBS.

[8,9] Peak-to-peak values of amplitudes were measured.

[10] This type of circuit is described in [4].

(and peak-to-peak values) versus frequency appears to be valid since all necessary precautions were taken to insure that the waveshape is the same for all frequencies. For example, capacitances C_a, C_b, $\cdots$ are chosen so that the product of capacitance and frequency is constant within 0.2 percent. Therefore, attenuation of the fundamental and harmonic components and the phase shifts of the harmonics relative to the fundamental remain constant for all calibration frequencies.

References

[1] F. L. Hermach, "Ac-dc comparators for audio-frequency current and voltage measurements of high accuracy," *IEEE Trans. Instrum. Meas.*, vol. IM-25, pp. 489-494, Dec. 1976.

[2] H. K. Schoenwetter, "An rms digital voltmeter/Calibrator for very-low frequencies," *IEEE Trans. Instrum. Meas.*, vol. IM-27, pp. 259-268, Sept. 1978.

[3] B. F. Field, "A fast response low-frequency voltmeter," *IEEE Trans. Instrum. Meas.*, vol. IM-27, pp. 368-372, Dec. 1978.

[4] P. Richman, "A new absolute ac voltage standard," in *IEEE Int. Conv. Rec.*, ot. 5, pp. 170-183, Mar. 1963.

APPENDIX A

Calibration Forms

Several forms have been prepared to facilitate the calibrations of rms voltmeters and the voltage and frequency response calibrations of ac voltage standards. These are:

(1) LOG SHEET

(2) WORK SHEET

(3) TABLE OF CALIBRATIONS

(4) REPORT OF TEST

These forms, as well as a brief description of the calibration procedure, are given in the following sections for each type of calibration. Items 3 and 4 and the summarized calibration procedure are sent to the customer, following a calibration.

Department of Commerce
National Bureau
of Standards

VOLTMETER CALIBRATIONS USING NBS AC VOLTMETER/CALIBRATOR

Equipment Mfr.____________________

LOG SHEET

Submitted by:____________________

Date_______Test No._______

Model No.__________ Ser. No.__________

Time	Frequency	Voltage range	Voltmeter readings (V_m)	Mean value		

Department of Commerce
National Bureau
of Standards

WORK SHEET

Date_____Test No._____

VOLTMETER CALIBRATIONS USING NBS AC VOLTMETER/CALIBRATOR

Equipment Mfr.______________________Model No.__________Ser. No.__________

Submitted by: ____

Frequency	Voltage range	$\bar{V}_{vm}$	V_c	Correction $V_c-\bar{V}_{vm}$	Standard deviation (s)	Number of readings (N)	Imprecision $\varepsilon_r=ts/\sqrt{N}$	Uncertainty of V_c (ε_c)	Total uncertainty $\pm(\varepsilon_c+\varepsilon_r)$	Confidence level used for t	

Calibration of Voltmeters

Calibrations are performed on rms-responding ac voltmeters using the ac voltage calibrator of the NBS AC Voltmeter/Calibrator. AC voltmeters can be calibrated at frequencies of 10, 5, 2, 1, 0.5, 0.2, and 0.1 Hz at any voltage level between 0.5 mV and 7 V.

The total uncertainty of a calibration is $\pm(\varepsilon_c + \varepsilon_r)$, where ε_c is the uncertainty of the ac calibrator voltage and ε_r is the imprecision of the calibration process. The estimated maximum uncertainty of the ac voltage calibrator is ±0.020 percent. The imprecision for a given calibration point is $ts/\sqrt{N}$, where t is Student's t for the selected confidence level, s is the standard deviation for a measurement, and N is the number of measurements (test runs) used to obtain the mean values of the measured quantities (voltmeter readings).

Unless otherwise requested by the customer, a single accuracy of calibration will be given for the corrections to the calibration points, based on a confidence level of 0.98 and the largest standard deviation encountered.

Department of Commerce
National Bureau
of Standards

TABLE OF CALIBRATIONS

Date________Test No.______

VOLTMETER CALIBRATIONS USING NBS AC VOLTMETER/CALIBRATOR

Equipment Mfr.______________________________

Submitted by:______________________________

Model No.________________Ser. No.________

Frequency	Voltage range	Average of voltmeter readings $\bar{V}_{vm}$	Correction to $\bar{V}_{vm}$	Number of readings (N)	Total uncertainty	Confidence level used for t

FORM NBS-259
(3-66)

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C. 20234

REPORT OF TEST

LOW FREQUENCY VOLTMETER

Manufacturer_______________
Model No.__________________
Serial No._______________

Submitted by

____
____

This voltmeter was tested using the ac voltage calibrator of the NBS AC Voltmeter/Calibrator at a room temperature of 23 ±1 °C.

The test points, average voltmeter readings, corrections,and total uncertainty are shown in the attached TABLE OF CALIBRATIONS. Also shown is the confidence level upon which the imprecision is based. The ac calibrator voltage uncertainty is treated totally as a systematic error. Unless otherwise indicated, the total uncertainty is based on the largest standard deviation encountered for any of the test points. Measurements on the test unit were made over a period of time which was too short to yield long-term stability information.

For the Director
National Engineering Laboratory

Barry A. Bell, Group Leader
Electronic Instrumentation and Metrology
Electrosystems Division

Test No. 722/__________
Order No.______________
Date: _________________
Attn: _________________

Department of Commerce
National Bureau
of Standards

LOG SHEET

Date______ Test No.______

CALIBRATIONS OF VOLTAGE STANDARD USING NBS AC VOLTMETER/CALIBRATOR

Equipment Mfr.______________________ Model No.__________ Ser. No.__________

Submitted by:____

Time	Nominal voltage	Frequency		Test unit		Calibrator			
		Test unit	Calibrator	DVM readings	Mean	DVM readings	Mean		

Department of Commerce
National Bureau
of Standards

WORK SHEET

Date________Test No.

CALIBRATIONS OF VOLTAGE STANDARD USING NBS AC VOLTMETER/CALIBRATOR

Equipment Mfr.____________________Model No.____________Serial No.__________

Submitted by:____

Nominal voltage	Frequency		Average of comparisons $\overline{V_C - V_T}$	DVM frequency response (ε_m)	Uncertainty of V_C (ε_c)	Standard deviation (s)	Number of comparisons (N)	Imprecision $\varepsilon_r = ts/\sqrt{N}$	Total uncertainty $\pm(\varepsilon_c + \varepsilon_m + \varepsilon_r)$	Confidence level used for t	
	Test unit	Calibrator									

Calibration of Voltage Standards

For each calibration point, the rms voltmeter (DVM) is used to compare the voltage V_T from the standard under test with the voltage V_c of the same nominal level from the ac voltage calibrator, choosing the calibrator frequency closest to that of the voltage being measured. After the test runs are made, the average $\overline{(V_c - V_T)}$ is formed for each calibration point, yielding corrections to the nominal voltage values of the test unit.

If the uncertainty of the calibrator voltage and the uncertainty caused by the DVM frequency response are denoted by ε_c and ε_m, respectively, the total uncertainty of a calibration point is given by $\pm(\varepsilon_c + \varepsilon_m + ts/\sqrt{N})$, where s is the standard deviation of a $(V_c - V_T)$ comparison and N is the number of comparisons (test runs). If the frequencies of the voltages being compared are within 5 percent of each other, ε_m is ±7 ppm. If the frequency difference is larger, the worst case value of ε_m, ±40 ppm, is used. The value assigned to ε_m is ±200 ppm (±0.02%); however, if the highest calibration accuracy is required by the customer, ε_c can be decreased to ±125 ppm by a special calibration of the NBS instrument.

Unless otherwise requested by the customer, a single accuracy of calibration will be given for the corrections to the calibration points, based on a confidence level of 0.98 and the largest standard deviation encountered.

Department of Commerce
National Bureau
of Standards

TABLE OF CALIBRATIONS

Date_____ Test No._____

CALIBRATIONS OF VOLTAGE STANDARD USING NBS
AC VOLTMETER/CALIBRATOR

Equipment Mfr.______________________________

Submitted by:______________________________

Model No.____________________ Ser. No.__________

Nominal voltage of standard	Frequency of standard	Correction to nominal voltage	Number of comparisons (N)	Total uncertainty	Confidence level used for t	

FORM NBS-259
(3-66)

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C. 20234

REPORT OF TEST

LOW FREQUENCY VOLTAGE STANDARD

Manufacturer______________
Model No.________________
Serial No.____________

Submitted by

____
____

This voltage standard was tested using the ac voltage calibrator and rms voltmeter (DVM) of the NBS AC Voltmeter/Calibrator at a room temperature of 23 ±1°C.

The test points (nominal voltage and frequency), corrections, and total uncertainty are shown in the attached TABLE OF CALIBRATIONS. Also shown is the confidence level upon which the imprecision is based. The uncertainty of the ac calibrator voltage and the uncertainty caused by the DVM frequency response are treated as systematic errors. Unless otherwise indicated, the total uncertainty is based on the largest standard deviation encountered for any of the test points. Measurements on the test unit were made over a period of time which was too short to yield long-term stability information.

For the Director
National Engineering Laboratory

Barry A. Bell, Group Leader
Electronic Instrumentation and Metrology
Electrosystems Division

Test No. 722/________________________
Order No.____________________________
Date_________________________________
Attn:________________________________

Department of Commerce
National Bureau
of Standards

LOG SHEET

Date________Test No._______

FREQUENCY RESPONSE CALIBRATIONS OF VOLTAGE STANDARD USING NBS AC VOLTMETER/CALIBRATOR

Equipment Mfr.________________________________Model No.__________Ser No.____________

Submitted by: ____

Time	Nominal voltage	Frequency	Voltage standard		Voltage standard			
			DVM readings	Mean	DVM readings	Mean		

Department of Commerce
National Bureau
of Standards

WORK SHEET

Date_____Test No._______

FREQUENCY RESPONSE CALIBRATIONS OF VOLTAGE STANDARD USING NBS AC VOLTMETER/CALIBRATOR

Equipment Mfr. ________________________ Model No._____________Ser. No.____________

Submitted by:____

Nominal voltage	Frequency	Test unit response ($V_f - V_{10}$)	DVM frequency response (ϵ_m)	Standard deviation of comparison (s)	Number of comparisons (N)	Imprecision $\epsilon_r = t/s\sqrt{N}$	Total uncertainty $\pm(\epsilon_m + \epsilon_r)$	Confidence level used for t			

Frequency Response Calibrations

These calibrations are made using the DVM to compare test unit voltages of frequency f with the 10 Hz value. After N comparisons, the quantities $\overline{(V_f - V_{10})}$ are computed for each test frequency, yielding the frequency response. The uncertainty of these calibration points is $\pm(\varepsilon_m + ts/\sqrt{N})$, where ε_m is ±40 ppm, the frequency response of the DVM, and s is the standard deviation of a comparison.

Unless otherwise requested by the customer, a single accuracy of calibration will be given for the frequency response, based on a confidence level of 0.98 and the largest standard deviation encountered.

Department of Commerce
National Bureau
of Standards

TABLE OF CALIBRATIONS

Date_______Test No._____

FREQUENCY RESPONSE CALIBRATIONS OF VOLTAGE STANDARD
USING NBS AC VOLTMETER/CALIBRATOR

Equipment Mfr.______________________________

Submitted by:______________________________

Model No._______________Ser. No._______________

Nominal voltage	Frequency	Frequency response (V_f-V_{10})	Number of comparisons (N)	Total uncertainty	Confidence level used for t	

FORM NBS-259
(3-68)

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C. 20234

REPORT OF TEST

LOW FREQUENCY VOLTAGE STANDARD

Manufacturer_______________
Model No.__________________
Serial No._________________

Submitted by

____
____

This voltage standard was tested for frequency response using the rms voltmeter (DVM) of the NBS AC Voltmeter/Calibrator at a room temperature of 23 ±1°C.

The test points (nominal voltage and frequency), corrections, and total uncertainty are shown in the attached TABLE OF CALIBRATIONS. Also shown is the confidence level upon which the imprecision is based. The uncertainty caused by the DVM frequency response is treated as a systematic error. Unless otherwise indicated, the total uncertainty is based on the largest standard deviation encountered for any of the test points. Measurements on the test unit were made over a period of time which was too short to yield long-term stability information.

For the Director
National Engineering Laboratory

Barry A. Bell, Group Leader
Electronic Instrumentation and Metrology
Electrosystems Division

Test No. 722/_______________
Order No. _______________
Date_____________________
Attn:____________________

APPENDIX B

Detailed Design of Voltage Calibrator

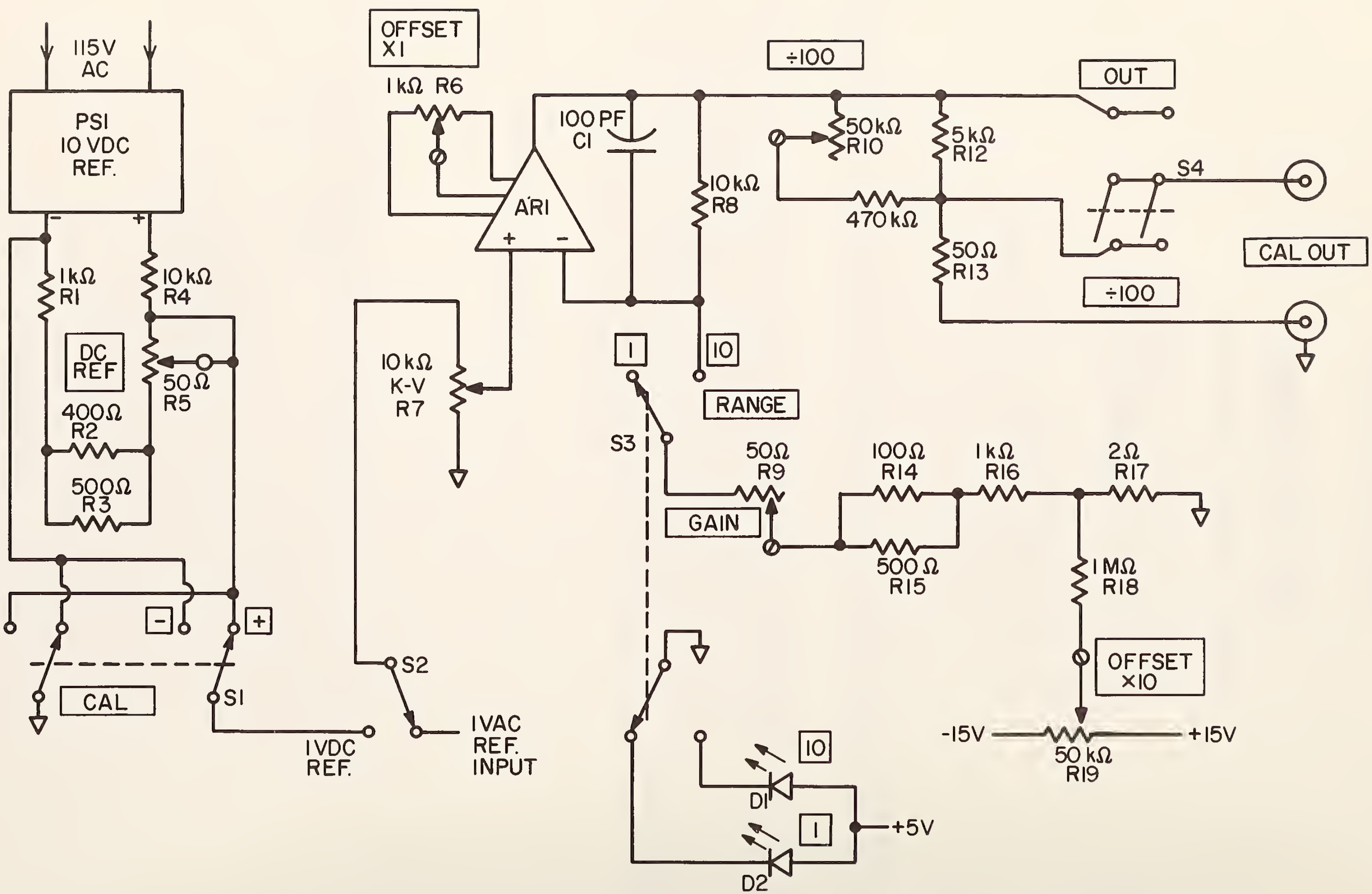
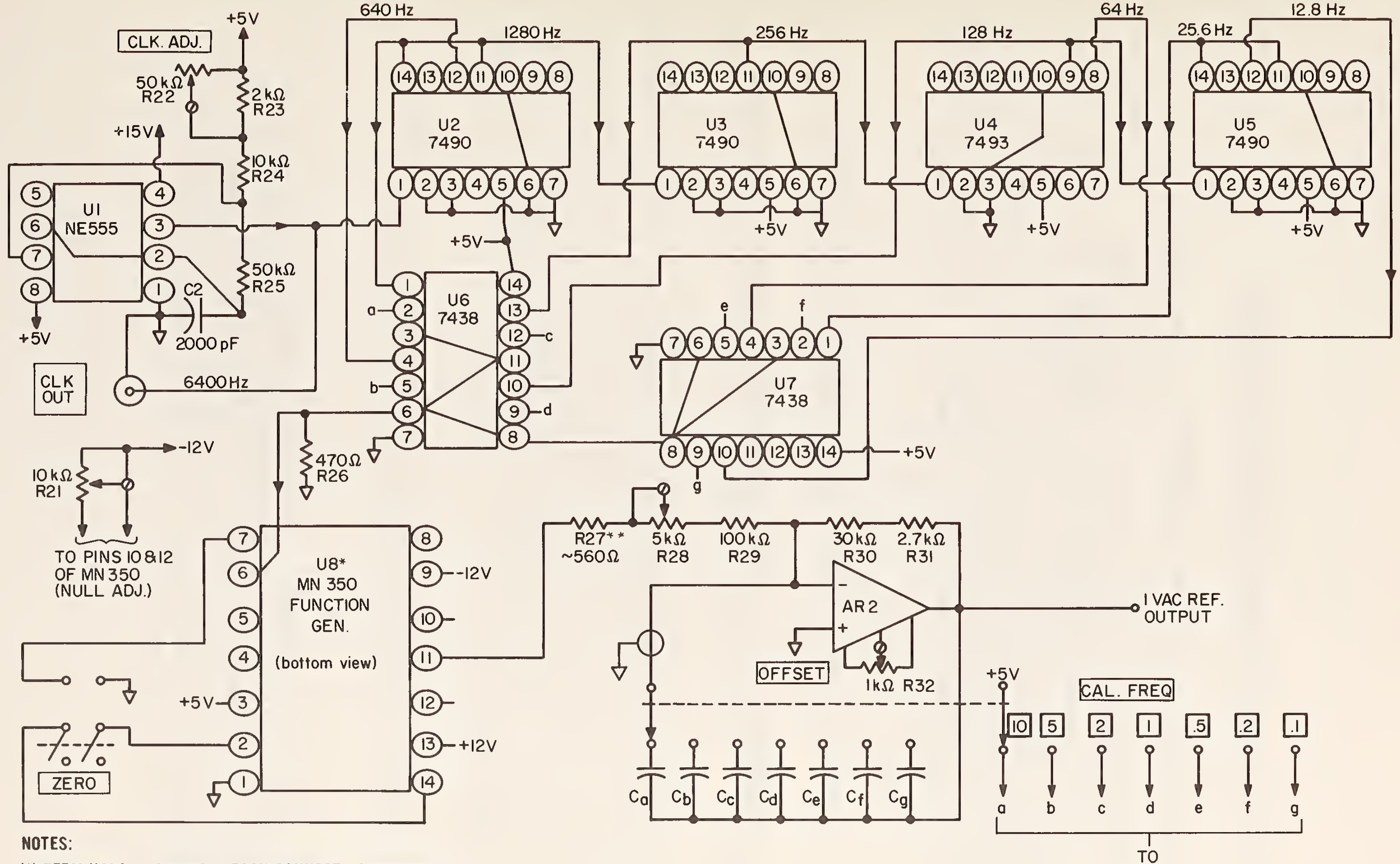


Figure B-1. Voltage calibrator. The 1 VAC reference is shown in figure B-2.



NOTES:

(1) TERMINALS a through g EACH CONNECT TO GROUND VIA 470Ω, SHUNTED BY 0.1μF

*MOUNTED ON 3×4×¼ in. Cu HEAT SINK VIA STEEL SPRING CLAMP

**TEMPERATURE COMPENSATING RESISTOR

Figure B-2. AC (sine-wave) reference.

Description of Components Used in Voltage Calibrator

Amplifiers AR1 and AR2 are Analog Devices Type 52K.[1]

Capacitors C1 and C2 are 5 percent silver mica types. Capacitor C2, or associated timing components, may need trimming to yield the desired clock frequency. The capacitors associated with AR2 should be trimmed so that (capacitance)(calibrator frequency) = constant, to within ±0.2 percent. Nominal values (μF) are: $C_a = 0.025$, $C_b = 0.05$, $C_c = 0.125$, $C_d = 0.25$, $C_e = 0.5$, $C_f = 1.25$, and $C_g = 2.5$. These polycarbonate capacitors have a rating of 100 V, 5% tolerance and ±0.1%/°C temperature coefficient. They were shunted with smaller capacitors (mica or polycarbonate) to obtain the desired capacitance ratios.

The function generator (U8) is Micro Networks Corporation Type MN350.

The dc reference (PS1) should have a dc stability of better than ±5 ppm/year.

Resistors R12 and R13 are 1W precision wirewound resistors with ±0.01% tolerance and temperature coefficients matched to within 2 ppm/°C. Two parallel 100 Ω resistors may be used for R13. All trimpots are 1W, 25 turn, panel mount type with ±150 ppm/°C temperature coefficient. Resistors R1 - R4, R8, R14 - R16, R23 - R25 and R28 - R30 are Vishay Resistive Systems Group Type 5102C. A non-inductive wirewound resistor was used for R17. R27 is a sensistor from Texas Instruments, whose value is determined from temperature tests. R7 is a general resistance Type DV-4007A K-V divider.

Switches S1 - S4 should have plastic sleeves on their handles to minimize thermal voltage generation at the switch contacts.

---

[1] Certain commercial equipment, instruments or materials are identified in this report in order to adequately specify procedures or special circuits. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipmment identified is necessarily the most suitable for the purpose.

APPENDIX C

Shipping and Fee Information

General shipping instructions are given in the latest issue of NBS Special Publication 250, "Calibration and Related Measurement Services of the National Bureau of Standards." Shipments of voltmeters and voltage sources for calibrations should be directed to

National Bureau of Standards
Electrosystems Division, MET B162
Rt. 270 and Quince Orchard Road
Gaithersburg, MD 20878 .

Current information on calibration fees is given in the NBS Special Publication 250 Appendix, which is updated every six months.

NBS-114A (REV. 2-8C)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBS TN 1182	2. Performing Organ. Report No.	3. Publication Date Sept. 1983

4. TITLE AND SUBTITLE

AC VOLTAGE CALIBRATIONS FOR THE 0.1 Hz to 10 Hz FREQUENCY RANGE

5. AUTHOR(S)

Howard K. Schoenwetter

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

Final

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

Sponsored in part by the
Calibration Coordination Group of the
Department of Defense

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The development of voltmeters to meet the need for rms voltage measurements in the infrasonic frequency range is discussed as well as the need to trace these measurements to the U.S. legal unit of voltage. A new method for supporting voltage measurements in the 0.1 Hz - 10 Hz range was described in a 1979 paper and is discussed further. The principles of the method are embodied in detailed procedures given for calibrating sine-wave voltage standards and rms voltmeters over the 0.1 Hz - 10 Hz frequency range, using the NBS AC Voltmeter/Calibrator. The sine-wave calibrator of this instrument, used for these calibrations, has an accuracy of 0.020 percent over the 0.5 mV - 7 V range.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

ac voltage calibrations; ac voltage calibrators; ac voltage standards; infrasonic voltage measurements; low-frequency voltage measurements; rms voltmeters

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